5-2014

Evacuation and Shelter in Place Modeling for a Release of Uranium Hexafluoride

Joseph B. Harris
East Tennessee State University

Evacuation and Shelter in Place Modeling for a Release of Uranium Hexafluoride

---

A thesis

presented to

the faculty of the Department of Geosciences

East Tennessee State University

In partial fulfillment

of the requirements for the degree

Masters of Science in Geosciences

with a concentration in Geospatial Analysis

---

by

Joseph Blake Harris

May 2014

Dr. Chris Gregg, Chair

Dr. Timothy Andrew Joyner, Co-Chair

Dr. Ingrid Luffman

Keywords: GIS, Hazards, ArcCASPER, Nuclear Fuel Services, Industrial, Meteorology, Preparedness, Modeling

ABSTRACT

Evacuation and Shelter in Place Modeling for a Release of Uranium Hexafluoride

by

Joseph Blake Harris

Evacuation and sheltering behaviors were modeled for a hypothetical release of uranium hexafluoride (UF_6) from Nuclear Fuel Services (NFS) in Erwin, Tennessee. NFS down-blends weapons grade Cold War-era nuclear fuel material and processes highly-enriched uranium occasionally using UF_6 onsite. Risk associated with a chemical release to the surrounding residential population was assessed by running 2 scenarios involving an airborne release of UF_6 to compare evacuation and sheltering in place actions as effective survival strategies. Risk is minimal and evacuation is recommended for people within a 2-mile radius of the release point. Shelter in place actions are recommended for all critical facilities that have the potential to be affected by a chemical release plume. Oak Ridge National Laboratory's Radiological Assessment System for Consequence Analysis and Capacity-Aware Shortest Path Evacuation Routing in conjunction with a geographic information system proved to be valuable technological tools in determining evacuation routing and exposure zones.

DEDICATION

This thesis is dedicated to my wife Balinda for her love and patience; to my parents for their unconditional love and support; to my grandmother for constantly reminding me of the importance of continuing my education; to Harnarine "Chris" Phillip for being my venting ground; and to Dr. T. Andrew Joyner for being my mentor.

ACKNOWLEDGEMENTS

First, I would like to thank Dr. Chris Gregg for serving as my committee chair along with Dr. T. Andrew Joyner and Dr. Ingrid Luffman for graciously agreeing to serve on my committee and for providing guidance during my thesis process. I would also like to express my sincere thanks and appreciation to Dr. Nathan Wood and Mr. Glenn Tilson for providing me a starting point for conducting my thesis research. I extend a special thank you to the faculty and staff of the East Tennessee State University Department of Geosciences for all of your support and encouragement.

TABLE OF CONTENTS

	Page
ABSTRACT…	2
DEDICATION	4
ACKNOWLEDGEMENTS….	5
LIST OF TABLES	8
LIST OF FIGURES	9
Chapter	
1. INTRODUCTION	10
Background Information	11
Past Industrial Accidents	11
History of Emergency Management in the United States	12
Protective Measures	14
Shelter in Place	14
Emergency Evacuation	14
Anthropogenic Health Impacts and Incidents	15
Uranium Hexafluoride Health Effects	16
Uranium Hexafluoride Incidents	17
Study Area	17
Erwin, Tennessee	17
Nuclear Fuel Services	21
Research Goals	21
2. EMERGENCY PREPAREDNESS ACTIONS FOR ERWIN, TENNESSEE IN RESPONSE TO A POTENTIAL TECHNOLOGICAL HAZARD	23
Abstract	23
Introduction	23

Background Information 24
Modeling and Software Applications in Emergency Preparedness 25
Research Objectives 26
Experimental 27
Data and Methods 27
Scenarios 30
Results 32
Meteorological and Plume Results 32
Scenario 1 Results 38
Scenario 2 Results 42
Discussion and Conclusion 45
References 46
3. DISCUSSION AND MAJOR FINDINGS 48
Study Limitations 49
Assumptions 50
Future Research 51
4. CONCLUSSION AND RECOMMENDATIONS 53
REFERENCES 54
APPENDICES 57
Appendix A: Meteorological Data for KTRI in Blountville, Tennessee 57
Appendix B: HF and U Concentration and Deposition Plumes 59
VITA 71

LIST OF TABLES

Table Page

2.1 UF_6 Cylinder Type and Volume 28

2.2 Comparison of Evacuation Model Methods 30

2.3 Average Wind Speed and Direction for 30 Years and 2012 33

2.4 Meteorological Averages by Season for the Year 2012 33

2.5 Risk Assessment Matrix for Erwin, Tennessee 38

2.6 Scenario 1 Shortest Path Algorithm Evacuation Time Distribution 39

2.7 Scenario 1 CASPER Algorithm Evacuation Time Distribution 41

2.8 Scenario 2 Shortest Path Algorithm Evacuation Time Distribution 42

2.9 Scenario 2 CASPER Algorithm Evacuation Time Distribution 44

LIST OF FIGURES

Figures Page

1.1 Emergency Management Cycle 11

1.2 Critical Facilities in Erwin, Tennessee 18

1.3 Total Population per Census Block 19

1.4 Total Housing Units per Census Block 19

1.5 Average Household Size per Census Block 20

1.6 Population Density per Square Mile 20

2.1 Major Arterial Roads and Safe Zones 31

2.2 UF_6 Plume Temperatures for All Seasons 34

2.3 UF_6 Plume Heights for All Seasons 35

2.4 HF and Uranium Concentration and Deposition Plume Models 37

2.5 Scenario 1 Evacuation Model Using the Shortest Path Algorithm 40

2.6 Scenario 1 Evacuation Model Using the CASPER Algorithm 41

2.7 Scenario 2 Evacuation Model Using the Shortest Path Algorithm 43

2.8 Scenario 2 Evacuation Model Using the CASPER Algorithm 44

CHAPTER 1

INTRODUCTION

Hazards are defined as any event, situation, or thing that poses a threat to human life and/or health and can cause damage to property and/or the environment (Harriss *et al.* 1978). In contrast, disasters are defined as crisis situations where the damage exceeds a community's ability to recover through routine resources (Quarantelli 1990). Industrial sites can present multiple hazards that endanger the health and safety of the adjacent population and multiple disasters at varying scales have been spawned from industrial hazards (e.g., Chernobyl, Three-Mile Island, Love Canal, Bhopal, Fukushima). Industrial hazards are perceived differently than other hazards because of the uncertainty associated with the hazard (Mitchell *et al.* 2007). Understanding the health effects and possible loss of life in such a disaster is necessary to help emergency managers determine how the effects can be mitigated by evacuation and sheltering in place strategies. An emergency evacuation is the removal of the populace from the threat or actual occurrence of a disaster's exposure zone (Georgiadou *et al.* 2007). In the context of industrial hazards representing a risk to surrounding residential areas, a shelter in place strategy involves the residential populace remaining indoors, securing all openings to the dwelling, turning off all ventilation, and taking shelter in the innermost room of the dwelling (Chan *et al.* 2007). Decisions concerning evacuation and shelter in place strategies require advanced planning and preparations on many levels. This type of predisaster planning is a key component of emergency preparedness, which is one of the 4 major phases of the emergency response management cycle (Figure 1.1).

Figure 1.1: Emergency Management Cycle. Adapted from the Federal Emergency Management Agency's Emergency Management Cycle.

Background Information

Past Industrial Accidents

The full effect of an industrial accident is usually not known until an accident occurs because industrial hazards are dynamic and present a multitude of uncertainties. The result is nonexistent or poorly planned emergency preparedness procedures, of which there are many examples including those in Flixborough, England; Seveso, Italy; and Bhopal, India (Garrik 1988). The Flixborough disaster occurred on June 1, 1974, when a bypass pipe ruptured releasing a vapor cloud of cyclohexane that interacted with an ignition source causing a massive explosion (Venart 2004). The disaster resulted in 28 deaths and widespread property damage to approximately 1,800 buildings (Venart 2004). In the Seveso disaster of 1976, rising temperatures inside a mixing reactor crossed a threshold that triggered the opening of a reactor valve, which resulted in the release of 2,3,7,8-tetrachlorodibenzodioxin (TCDD) that exposed over 37,000 people to the chemical (Bertazzi *et al.* 1998). The deadliest industrial accident in history occurred in Bhopal in December 1984. Over 100,000 people were exposed to hazardous materials after a gas leak occurred at a pesticide manufacturing plant (Bowonder 1985). This resulted in the death of approximately 3,800 people with thousands more suffering acute and chronic health effects from the incident (Dhara and Dhara 2002; MacKenzie 2002). Collectively, these incidents caused government agencies and emergency managers to shift their attention to industrial sites where emergency preparedness procedures became a priority.

<u>History of Emergency Management in the United States</u>

Emergency management in the United States dates back to the early 19th century when the federal government passed the Congressional Act of 1803, which provided financial assistance to a New Hampshire town devastated by fire. However, the focus on emergency preparedness was not fully conceptualized until the Cold War began in the mid-20th century. The Office of Defense Mobilization was created during this time for the purpose of mobilizing and stockpiling critical materials that would be needed during an attack. Emergency preparedness was limited to Civil Defense purposes until the 1960s when the Office of Emergency Preparedness was formed to manage natural disasters. By the 1970s, over 100 federal agencies where involved in some aspect of emergency management including emergency preparedness and this led to the creation of one centralized organization known as the Federal Emergency Management Agency (FEMA). The primary goal of FEMA was to prepare for and respond to anthropogenic and natural disasters. FEMA encountered several incidents that demonstrated the complexities involved in emergency management during the organization’s infancy such as the Love Canal toxic waste disaster in Niagara Falls, New York and the partial core meltdown on Three Mile Island in Pennsylvania.

These disasters along with the threat posed from nuclear power plants in the 1970s spurred FEMA and the Nuclear Regulatory Commission (NRC) to focus more on the emergency preparedness aspect of disasters, which led to the creation of evacuation plans for populations within a 10 mile (16.1 km) radius of nuclear power plants (Urbanik 2000). This zone of 10 miles (16.1 km) is known as an Emergency Planning Zone (EPZ) and is defined as the area where plume inhalation is expected to exceed the Environmental Protection Agency’s Action Guides (Collins and Galpin 1978; Podolak and Sanders 1988). Spellman and Stoudt (2011) noted that a complete evacuation of the EPZ is not always necessary because the released material moves in the direction of the prevailing wind and will become more diluted as it travels away from the point of release. As a general rule, it is recommended that everyone be evacuated who is within a 2 mile (3.2 km) radius of the release point as well as anyone within a 5 mile (8 km) radius downwind and adjacent to the projected plume path (Spellman and Stoudt 2011). Adjacency accounts for a potential shift in wind speed or fluctuation in wind direction – 2 of the multiple complex and dynamic parameters that define industrial hazards and increase uncertainty for emergency planning and preparedness. The shelter in place strategy is encouraged for those remaining within the 5 mile radius as well as for those outside the 5 mile radius but within the 10 mile EPZ. Evacuation decisions for populations within the 5 to 10 mile radius are continuously evaluated as the incident progresses, allowing those who are in immediate danger to evacuate quickly with minimal traffic congestion (Spellman and Stoudt 2011).

Protective Measures

Protective measures are actions taken to reduce the population's exposure to hazardous material that has been released into the environment (Hans and Sell 1974). Two types of protective actions are involved in the emergency preparation phase for an anthropogenic hazard. These 2 actions are emergency evacuation and sheltering in place. The selection of one action or the combination of both actions are dependent upon the type of disaster, socio-demographic attributes, and distance from the incident (Hans and Sell 1974).

Shelter in Place

A shelter in place action is often an effective approach in protecting the public from adverse health effects during and immediately following a chemical release (Chan *et al.* 2007). Ideally, a population that is ordered to shelter in place remains indoors, secures all openings to the dwelling, turns off all ventilation , and takes shelter in the innermost room of the dwelling (Chan *et al.* 2007). In addition to these actions, it is recommended by the Department of Homeland Security to take shelter in the innermost room above ground due to the ability of some chemicals to penetrate into basements. Sealing cracks in the doors and windows of the innermost room is also recommended by using duct tape and heavy sheeting. Sheltering in place reduces the individual's exposure to a hazardous chemical as well as the confusion and chaos often associated with a large-scale evacuation (Jetter and Whitfield 2005).

Emergency Evacuation

The impetus for emergency evacuation is most often the occurrence or imminent threat of a hazard when there is sufficient time to evacuate to a safe or safer place and sheltering in place is unlikely to provide sufficient assurance of protection. Past evacuations demonstrated that without proper planning emergency evacuations will not occur in an efficient manner. Common examples of poorly planned evacuations occur when people are ordered to evacuate when it is unnecessary or when people who should evacuate ignore evacuation orders (Flynn 1979). On March 28, 1979, the governor of Pennsylvania advised that preschool children and pregnant women within a 5-mile radius of the Three Mile Island nuclear power generating station should evacuate the area while everyone else up to a 10-mile radius should pursue a shelter in place strategy. Most ignored this and decided to evacuate resulting in citizens evacuating from a radius of 25 miles (Flynn 1979). In 2005 citizens of New Orleans, Louisiana were ordered to evacuate the city during the arrival of Hurricane Katrina, but many remained due to their inability or unwillingness to evacuate (Elder *et al.* 2007).

Anthropogenic Health Impacts and Incidents

Thousands of hazardous chemical releases occur annually within the United States (Zimmerman *et al.* 2008). These releases can cause a number of acute and chronic health problems for affected populations. Acute (short-term) health effects are caused by the initial exposure to a chemical hazard and require immediate medical attention, while chronic (long-term) health effects are manifested slowly over time after the initial contact to hazardous chemicals.

Uranium Hexafluoride Health Effects

Uranium hexafluoride (UF_6) is a chemical compound that is used at fabrication facilities to create fuel for nuclear reactors. UF_6 reacts with water or water vapor forming hydrogen fluoride (HF) and uranyl fluoride (UO_2F_2).

$$UF_6 + 2H_2O = UO_2F_2 + 4HF + Heat$$

Heat that is released from the chemical reaction causes these chemicals to become buoyant and rise in a plume (McGuire 1991). The health effects associated with exposure to UF_6, HF, and UO_2F_2 chemicals are dependent upon the amount and length of time of exposure as well as the health and age of the individual exposed (McGuire 1991). Of the 3 chemicals, HF can pose the highest threat to human beings Exposure to HF can cause several acute effects including death related to cardiac or respiratory failure. Inhalation of HF can cause pulmonary edema and severe irritation of the respiratory system. Eye or skin exposure to HF can result in severe ocular irritation and dermal burns. Chronic effects associated with HF exposure include damage to the liver, kidneys and lungs; irritation and congestion of the nose, throat, and bronchi; increased bone density; and anemia and hypersensitivity (Thiessen *et al.* 1988).

Emergency Response Planning Guides (ERPG) provide a guideline for the dose exposure needed to cause health effects for a 1-hour exposure time. There are 3 tiers of the ERPG: ERPG-1 is the maximum dose to which a human being can be exposed without experiencing any negative health effects; ERP-2 is the maximum hourly dose a human can be exposed to without experiencing irreversible serious health effects; and ERP-3 is the maximum hourly dose a human can be exposed to without life-threatening health effects. The ERP-1 range for HF is 0.001 to 2 ppm, ERP-2 is 2 to 20ppm, ERP-3 is 20 to 50ppm and anything above 50 ppm can cause life threatening health effects.

Uranium Hexafluoride Incidents

There have been several incidents involving UF_6 chemicals including a release of UF_6 at the Sequoyah Fuels Corporation Facility in Gore, Oklahoma. This accident occurred in 1986 when an over-loaded 14 ton cylinder ruptured during a reheating process attempting to remove excess UF_6. One individual died from inhalation of HF with an additional 31 workers experiencing short-term kidney damage from HF exposure (Shum *et al.* 1986). In 1978 a cylinder ruptured at the Portsmouth Gaseous Diffusion Plant after it was accidentally dropped in the storage yard releasing over 6.5 tons of UF_6 (DOE 2000). UF_6 incidents are rare occurrences and it is therefore unlikely that a major catastrophe will occur again soon, but these incidents highlight the potential for future UF_6 incidents and the need to have contingency measures in place that mitigate exposure.

Study Area

Erwin, Tennessee

The town of Erwin, located in the Appalachian Mountains of Northeast Tennessee, is situated along the border of the Cherokee National Forest in Unicoi County approximately 15 miles south of Johnson City. Unicoi County contains residential, industrial, commercial, and farming areas. Erwin has a population of 6,097 and Unicoi County has a population of 18, 313 (US Census 2010). Erwin would benefit from elevated levels of emergency preparedness based on its proximity to a potentially dangerous rail yard and an industrial site, Nuclear Fuel Services (NFS) (Figure 1.2). Approximately 35% of the citizens within Unicoi County live within 2 miles of NFS (Figure 1.3). This places approximately 3,000 housing units within a 2-mile radius of NFS with an average household size of 2.1 persons (Figures 1.4 and 1.5). Population density is centered in the downtown area of Erwin (Figure 1.6). Several densely populated critical facilities (e.g. schools, nursing homes, and hospitals) are also situated near the NFS facility (Figure 1.2). Erwin Health Care Center and Love Chapel Elementary School (it is important to note that this school was closed on August 2012 due to sinkhole hazards) are located less than a mile from the site, while Unicoi County Middle School, Unicoi County High School, Unicoi County Memorial Hospital, and the Center on Aging and Health are situated within 2 miles of NFS (Figure 1.2).

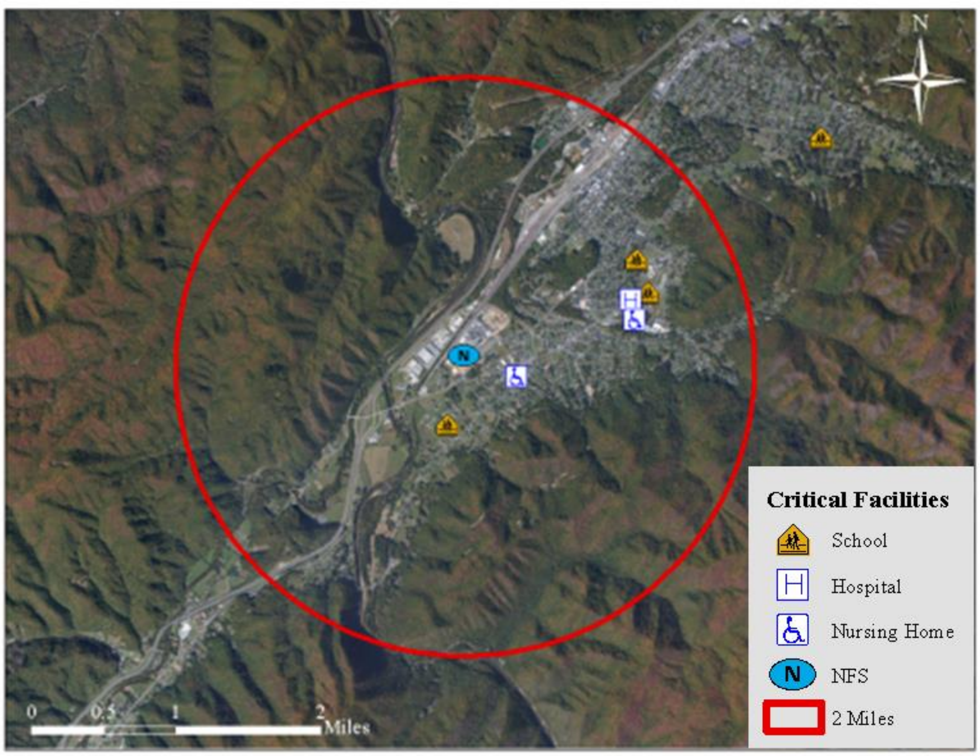


Figure 1.2: Critical Facilities in Erwin, Tennessee. All critical facilities within 2 miles of Nuclear Fuel Services.

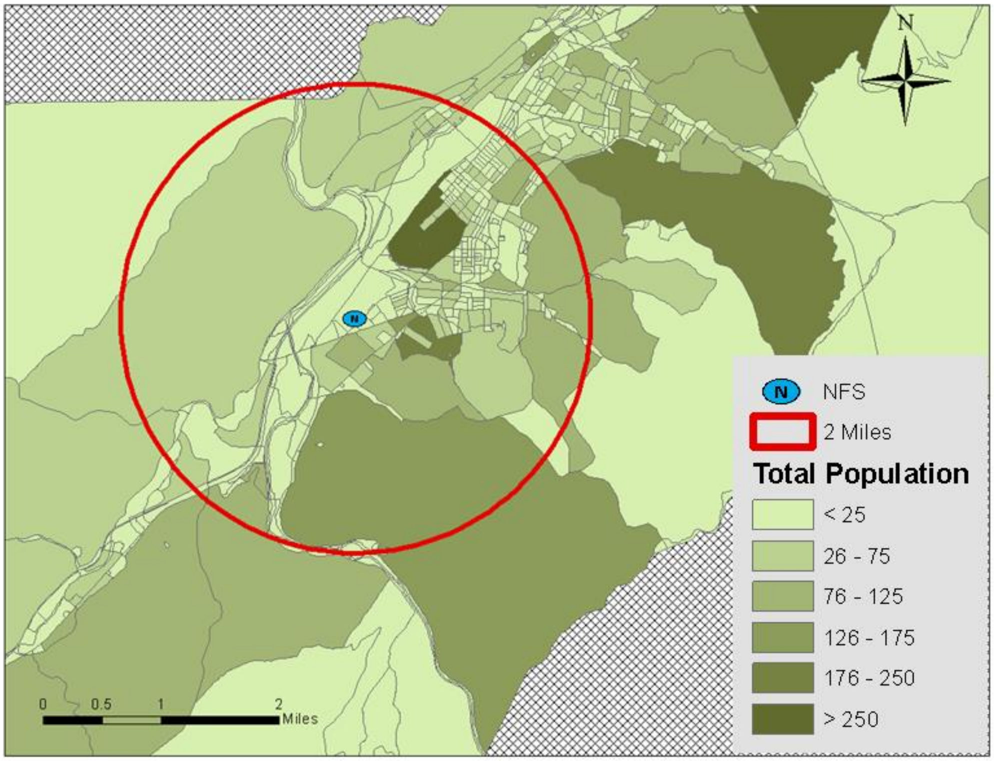


Figure 1.3: Total Population per Census Block

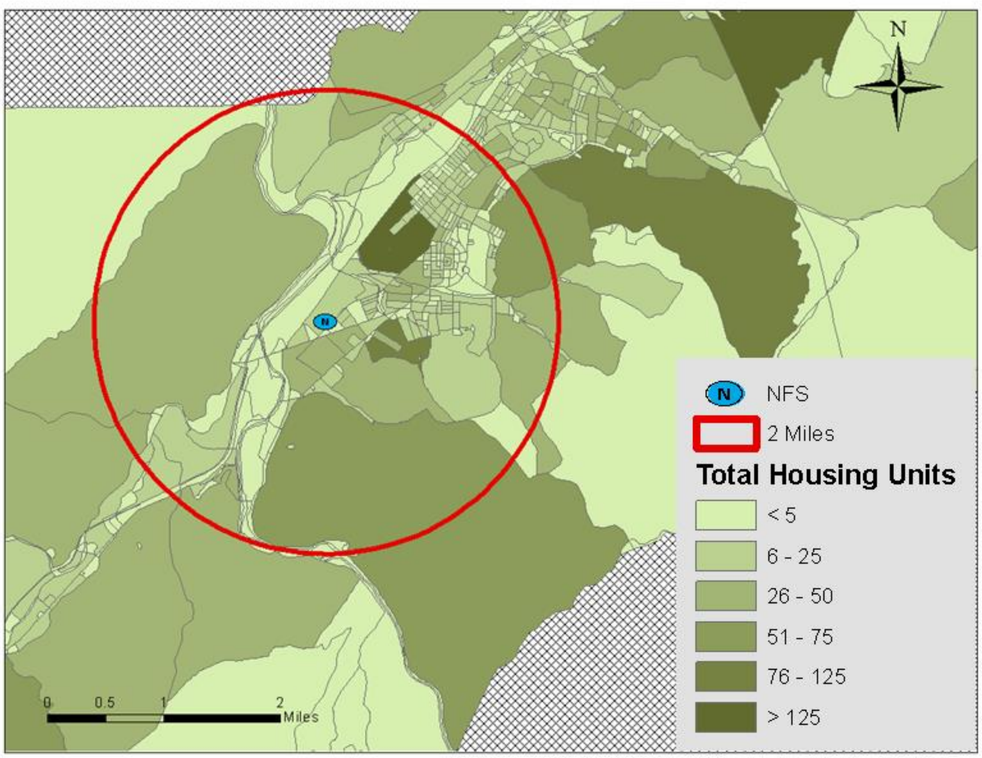


Figure 1.4: Total Housing Units per Census Block

Figure 1.5: Average Household Size per Census Block

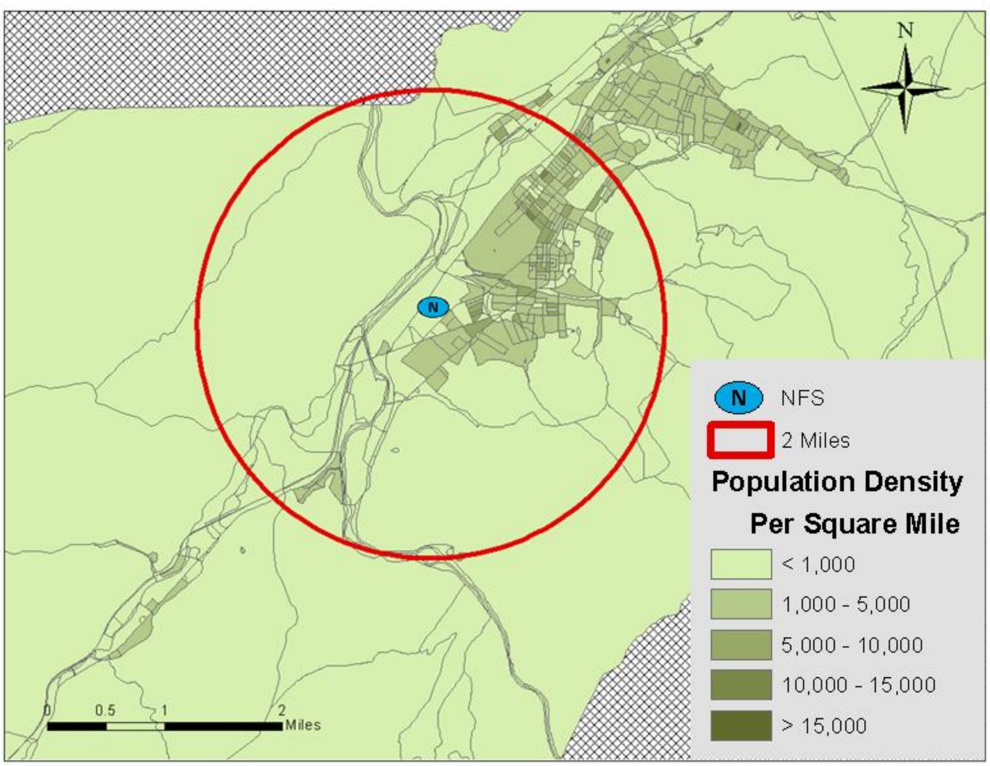


Figure 1.6: Population Density per Square Mile. Population density of Erwin, Tennessee per census blocks.

Nuclear Fuel Services

NFS is a nuclear fuel manufacturing plant located on the south side of Erwin, Tennessee. Its primary functions are the down-blending of Cold War-era nuclear fuel material into useable low-enriched uranium (LEU) for the Tennessee Valley Authority's (TVA) commercial reactors and processing highly-enriched uranium (HEU) into useable nuclear fuel for the United States Navy's nuclear fleet. NFS began fuel fabrication services in 1959 and has operated continuously since (US NRC 2014). To date, NFS has never had an occurrence severe enough to require the evacuation of Erwin, but there have been numerous incidents since down-blending began at the NFS site. On March 6, 2006, nine gallons of highly enriched uranium (HEU) leaked onto the plant floor (US NRC 2007). A fire occurred on November 14, 2009, within the cylinder sublimation station (US NRC 2009). A U.S. Nuclear Regulatory Event Notification Report filed in January 2010 in response to the 2009 fire noted that there may be over-pressurized UF_6 containers located on site at NFS (US NRC 2010). On January 9, 2012, NFS experienced a nitric acid leak that expelled approximately 300 gallons of the chemical (US NRC 2012). All of these incidents were contained on site and did not endanger any citizens of the community, but the potential for future incidents should be considered when developing components of an emergency preparedness plan for Erwin residents and NFS. UF_6 may or may not still be on the premises, but based on previous incident reports the facility at some point in time had UF_6 and a hypothetical scenario is being proposed based on UF_6.

Research Goals

Preparing for a possible disaster is an important aspect of emergency management and it is imperative to be proactive in understanding a potential threat to speed up response times and mitigate potential injury and loss of life. Completion of this study will 1) determine the risk associated with a chemical release to the population adjacent to NFS, 2) determine the effectiveness of mandatory evacuation and/or shelter in place strategies for the community, 3) demonstrate the usefulness of available software in the emergency preparedness phase as it relates to modeling evacuation and sheltering behaviors, and 4) identify critical facilities (e.g., schools, hospitals, nursing homes) that are at higher risk than the regular populace. This thesis does not imply that a disaster will occur at NFS but examines the possibility of a hypothetical disaster and illustrates the utility of various models in analyzing the impact of exposure to a potential hazard and the adequacy of current infrastructure in facilitating a timely evacuation and/or shelter in place action. Preparing for the possibility of a potential exposure to either UF_6 or any other airborne chemical may reduce the loss of human lives and establish actionable protocol for Erwin, Tennessee. In contrast, establishing that UF_6 does not represent a substantial risk might go a long way in assuring residents in Erwin that while UF_6 may be a past, present, or future hazard onsite, it is unlikely to pose a threat to people offsite.

CHAPTER 2

EMERGENCY PREPAREDNESS ACTIONS FOR ERWIN, TENNESSEE IN RESPONSE TO A POTENTIAL TECHNOLOGICAL HAZARD

Joseph B. Harris, Dr. Chris Gregg, Dr. T. Andrew Joyner and Dr. Ingrid Luffman

Department of Geosciences, College of Arts and Sciences, East Tennessee State University

Johnson City, Tennessee 37614, United States

Abstract - The protective measures of evacuation and shelter in place actions were analyzed by identifying the population at risk using historical meteorological data to create uranium hexafluoride (UF_6) plume models. Two hypothetical scenarios used plume models to determine if the infrastructure was sufficient to accommodate a mandatory evacuation and to identify the critical facilities and/or residential facilities that would be needed to shelter in place. Overall, evacuations from the affected area were efficient and accomplished in a timely manner, and all critical facilities that would benefit from sheltering in place were identified. The study concluded that the risk of release of UF_6 from a cylinder rupture is low and that the impact of an incident would be minor. Nevertheless, an emergency action protocol should be implemented to provide advanced preparation for the community.

1. Introduction

Industrial facilities that processes hazardous materials have the potential to endanger the health and safety of the nearby population. Communities therefore need to remain vigilant and develop emergency protocols that provide protection in the event of release. This type of planning is a key component of emergency preparedness, which is one of the four major phases of the emergency management cycle. Community and individual response to releases of hazardous materials often involve evacuation and sheltering in place as a means to limit exposure to the hazard agent.

1.1 Background Information

The town of Erwin, located in the Appalachian Mountains of Northeast Tennessee, is situated near the Cherokee National Forest and the Nolichucky River approximately 15 miles south of Johnson City, Tennessee and 45 miles north of Asheville, North Carolina. Nuclear Fuel Service (NFS) is a uranium fuel fabrication plant that was built and has operated continuously within the city limits of Erwin since 1959. NFS down-blends Cold War-era nuclear fuel material into useable low-enriched uranium (LEU) for the Tennessee Valley Authority's (TVA) commercial reactors. NFS also processes highly-enriched uranium (HEU) into useable nuclear fuel for the United States Navy's nuclear fleet. One of the major chemical compounds used at fabrication facilities to create fuel for nuclear reactors is uranium hexafluoride (UF_6). When released into the atmosphere, UF_6 will react with the water vapor present in the environment forming hydrogen fluoride (HF) and uranyl fluoride (UO_2F_2) [1]. Human exposure to HF gas can cause chronic and acute health effects ranging from skin burns to lung damage [2]. The health effects associated with HF gas are dependent upon the amount and length of exposure to the chemical [2,3]. Emergency Response Planning Guides (ERPG) estimate that a dose greater than 50 ppm over a one hour period have the potential to induce life threatening health effects. Limiting a population's exposure time to the chemical is key to mitigating injuries and loss of life [4]. This can be accomplished through protective measures such as an evacuation or sheltering in place [4].

Evacuation is defined as the removal of the populace from the threat, or actual occurrence of, a hazardous exposure zone [5]. Sheltering in place action is defined as finding shelter indoors, securing all openings to the dwelling, turning off all ventilation, and taking shelter in the innermost room of the dwelling [6]. These actions can be used independently or in combination with each other to mitigate injuries and loss of life to the populace in the affected area. An emergency plan can be constructed that implements these protective measures using current modeling software available to researchers and emergency management.

1.2 Modeling and Software Applications in Emergency Preparedness

A geographic information system (GIS) integrates both hardware and software to aid in analyzing, capturing, managing and displaying geographic data [7]. In the context of emergency preparedness, a GIS is a valuable tool because it has the capability to analyze a network dataset to determine if road networks are capable of handling evacuation traffic loads, identifying effective evacuation routes, and identifying safe zones away from hazard zones [8]. A GIS is not limited to just network analysis. It has the ability to model complex scenarios when the hazard itself is viewed in relation to spatial data [8].

Capacity-Aware Shortest Path Evacuation Routing (ArcCASPER) is a network analyst tool used in conjunction with a GIS (specifically ArcMap 10.0) to produce evacuation routes to the nearest safe area incorporating typical road capacity and travel times to reduce evacuation times and congestion [9]. ArcCASPER uses three separate algorithms to allow the user the ability to compare the results and identify the most effective method. These algorithms are shortest path, Capacity Constrained Route Planning (CCRP), and Capacity-Aware Shortest Path Evacuation Routing (CASPER). The shortest path method is the fastest of the three methods, but ignores road capacity and has very low accuracy [9]. The CCRP algorithm prioritizes evacuees based on their distance from the safe zone, by giving those with longer travel times the ability to divert to alternate routes until that roadway is at capacity [9]. The CASPER algorithm takes evacuees with the longest travel times and assigns them to a shortest path. Edge costs (amount of time it takes to travel a segment of road) are constantly updated to ensure global evacuation times are at a minimum [9].

Radiological Assessment System for Consequence Analysis (RASCAL) version 4.3 is an emergency response consequence assessment tool developed by Oak Ridge National Laboratory. The United States Nuclear Regulatory Commission makes dose and consequence projections in the event of a radiological emergency and these serve to inform the RASCAL model [10]. RASCAL evaluates meteorological and atmospheric conditions around nuclear facilities to provide an assessment of the incident (e.g., plume models, plume height, plume temperatures) [10]. ArcCASPER and RASCAL alone are valuable tools to a user, but combined they become a viable option in preparing actionable protocols for communities that may be at risk to a hazard and who desire to mitigate exposure by evacuation and sheltering.

1.3 Research Objectives

The objectives of this study are to 1) demonstrate the utility of evacuation modeling for industrial hazards producing offsite airborne hazards, 2) determine if mandatory evacuations are preferable over sheltering in place, and 3) determine if the current infrastructure (roads) is sufficient to accommodate a mandatory evacuation. Depending on the intensity (rate of release), volume, and dose of UF_6 released, it may be better for citizens within the area to opt for a shelter in place action over a mandatory evacuation action, but no information is currently available to assist in making this crucial decision. Examination of the infrastructure will assist in determining the time it takes to evacuate an area, possible congestion points that may halt evacuation, and identification of timely evacuation routes.

2. Experimental

2.1 Data and Methods

When evaluating emergency preparedness solutions involving a UF_6 release, it is important to take into account the current meteorological conditions since this will determine if evacuation and/ or a shelter in place strategy is necessary for the community surrounding the industrial site. For example, a strong northerly wind indicates that a UF_6 plume will be carried in a southern direction affecting those who are located south of the site while conversely a southerly wind will carry a UF_6 in a northern direction affecting the community north of the site. RASCAL version 4.3 was used because the software allows for the input of meteorological data from the National Oceanic and Atmospheric Administration (NOAA) weather station located at the Tri City Regional Airport (KTRI) in Blountville, Tennessee – the closest reliable weather station in the area. The variables used in this process were wind speed, wind direction, estimated atmospheric stability, precipitation type, ambient air temperature, air pressure, and relative humidity. For the purpose of this study, the averages of historical meteorological data for the four calendar seasons (spring, summer, autumn, and winter) along with the yearly averages for the year 2012 were calculated to determine if potential differences in dispersion occur seasonally. A 30 year period of averages for wind speed and direction were calculated and compared with the averages for the year 2012 to determine if the 2012 averages were above or below the normal averages for the area. Spring was defined as March, April and May; Summer as June, July, and August; Autumn as September, October, and November; and Winter as December, January, and February. These data were then combined with the cylinder inventory volume (Table 2.1) and release rate for liquid UF_6 based on a cylinder rupture with a release fraction of 0.65, a release rate of 32 kg/s, and a cylinder enrichment level of 5% [10] to calculate the transportation, dispersion, and deposition of material for a one hour period from the initial release start time. This process created twelve plume models for each season and one plume model for yearly averages for hydrogen fluoride (HF) concentration, HF deposition, uranium (U) concentration, and U deposition which were imported into ArcMap 10.0 to determine the area that would be affected.

Table 2.1: UF_6 Cylinder Type and Volume [10]

Cylinder Type	**Volume of UF_6 (kg)**
Model 30A and 30B (2.5 ton)	2,277
Model 48A and 48X (10 ton)	9,539
Model 48Y, 48G, 48F and 48H (14 ton)	12,338

ArcMap 10.0 is the feature program within a geographic information system (GIS) created by the Environmental Systems Research Institute (ESRI) and is used for map creation, spatial and statistical analysis, data editing and creation, and GIS dataset management. A GIS was used to import plume data and identify areas that are affected by a UF_6 chemical release. A dataset of Unicoi County, Tennessee at the census block level that included total population and housing units was used to determine the average household size per census block. The location of NFS and all critical facilities within a two mile radius (EPZ) of NFS were mapped within the GIS. A buffer zone of two miles was created to aid in determining areas that require mandatory evacuation and facilities that would benefit from a shelter in place action [11].

For evacuation modeling, ArcCASPER (Table 2.2) requires a network dataset (e.g., interconnected roadways with intersections nodes) to be built and subsequent analyses were performed on that dataset. Two road networks of Unicoi County were digitized using an ESRI road basemap of Unicoi County and two network datasets were created based on the area roads. One dataset included the entire road network for Unicoi County while the other dataset excluded a segment of Tennessee Highway 107. A capacity field was added to the dataset to account for the number of lanes contained in each road segment. Locations of the populace to be evacuated within two miles of NFS and the population downwind and adjacent to the plume were created using population totals at the census block level. Locations of the safe zones were determined by the plume direction. Some safe zone locations were located within the EPZ, as the main purposes of evacuation are to route evacuees to the nearest road that would allow for the quick departure from the chemical plume or to the nearest access point to United State Interstate 26 where emergency management personnel would have the ability to direct traffic out of harm's way more quickly than on state roads. This is achievable because of an increase in both road capacity and speed limit. The ArcCASPER process was compiled using the yearly average plume model to identify the areas at risk involving two hypothetical scenarios devised to determine the effectiveness of a mass evacuation.

Table 2.2: Comparison of Evacuation Model Methods

Method	Advantages	Disadvantages
ArcCASPER	• Three different model algorithms available (Shortest Path, CASPER, and Capacity Constrained Route Planner). • Easy to validate and reproduce models. • Output allows for the visualization of edge statistics and route costs.	• Only compatible with the network analyst tool within ArcMap. • Requires a network with no accuracy, alignment, or topological errors to function properly.
Agent Based Modeling	• Models are close to reality. • Ability to control agent behavior to simulate "real life" situations.	• Difficult to validate and reproduce the model. • Amount of data needed to influence agent behavior can be overwhelming. • Models can be difficult to disseminate.
Least Cost Distance Modeling	• Evacuation routing is not constrained to a road network allowing for different transportation options. • Slope and land cover data can be used to calculate travel costs. • Compatible with a GIS.	• Travel cost is calculated for each raster cell which requires high resolution data to ensure accurate travel times. • Limited to shortest path approach.

2.2 Scenarios

Two hypothetical evacuation model scenarios were created for this study. Scenario number one uses the entire road network for the evacuation model. Scenario number two simulates a train restricting the movement of cars on a segment of Tennessee 107 which is a main arterial road providing ingress and egress to and from Erwin. Erwin is unique in that the rail system runs parallel to US HWY 26 and in between the highway and the town. This creates limited evacuation points if a train happens to stop on the tracks in the downtown area. Two different algorithms (shortest path and CASPER) were used for each scenario to determine the effectiveness of the CASPER algorithm in evacuation modeling. Safe zone locations for each model were determined to be Tennessee Highway 81 (Jonesborough Road) to the northwest, Tennessee Highway 352 (Temple Hill Road) to the south, Tennessee Highway 107 (North Main Avenue) to the north, US Highway 26 access on 2nd Street, and US Highway 26 access on Jackson Love Highway (Figure 2.1). A total of 250 evacuee locations were created using population totals at the census block level creating an evacuation size of 6,069 people.

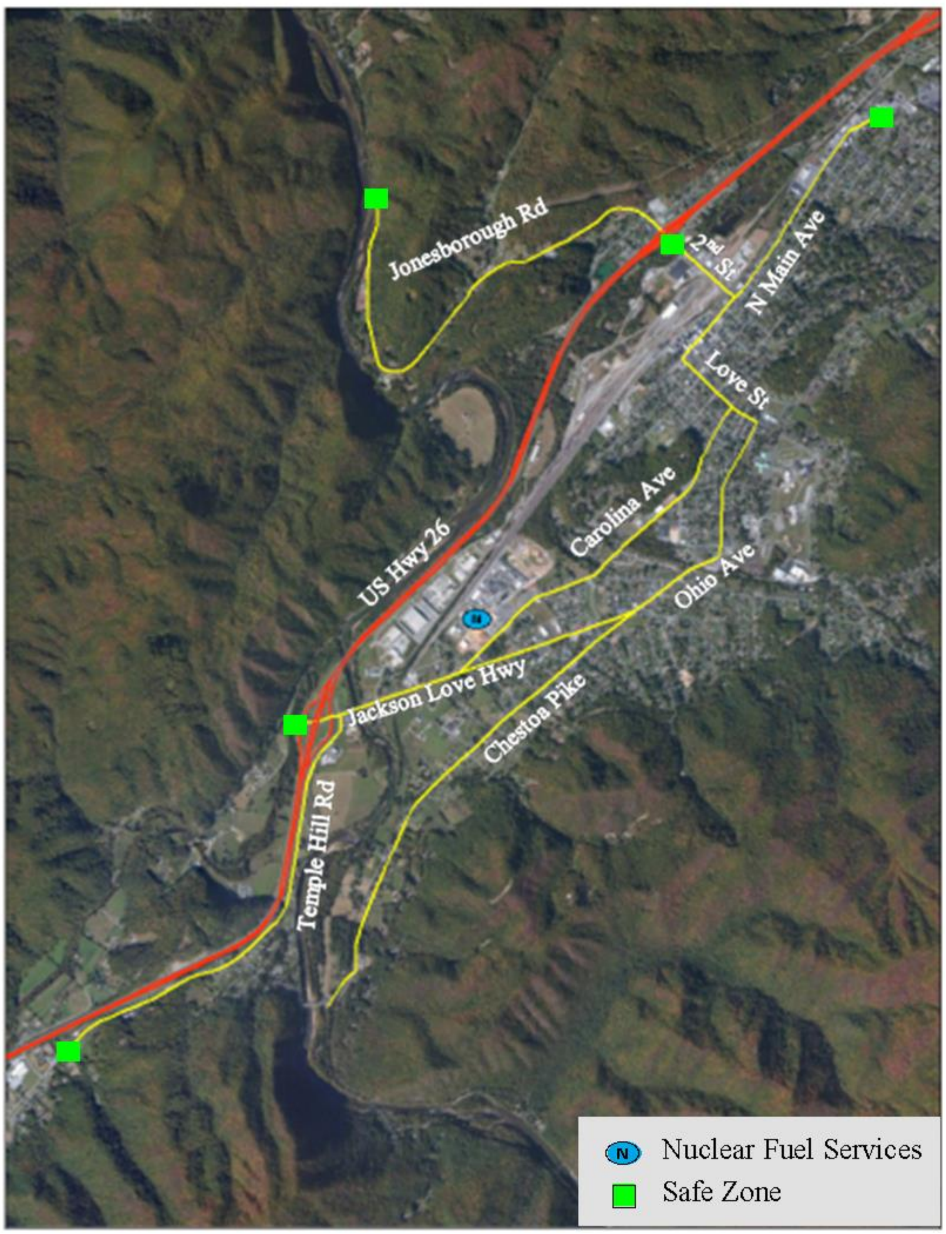


Figure 2.1: Major Arterial Roads and Safe Zones

3. Results

3.1 Meteorological and Plume Results

Average wind direction for the year 2012 were comparable to the average wind directions for the historical 30 year period while average wind speeds were found to be significantly higher for the year 2012 (T-test results of 7.84; $p < 0.01$) (Table 2.3). Average wind speed for the seasons in the year 2012 ranged from 6.2 mph (9.9 km/h) to 8.4 mph (13.5 km/h) with wind direction ranging from 262° to 276° (Table 2.4 and Appendix A). Average air temperature ranged from 41.7°F (5.4°C) to 72.7°F (22.6°C) with the winter season representing the coldest season and summer representing the warmest season (Table 2.4). Barometric pressure for the seasons was fairly consistent for three of the four seasons. The average barometric pressure was 1018mb and the summer season averaged 1015mb (Table 2.4). The spring season has the lowest relative humidity with an average of 70.6% (Table 2.4). Relative humidity in the other seasons ranged from 75.8% to 76.9% with winter having the highest percentage (Table 2.4). Results for each season are described in the paragraphs below.

Table 2.3: Average Wind Speed and Direction for 30 Years and 2012

30 Year Wind Averages			2012 Wind Averages		
Season	**Wind Speed**	**Wind Direction**	**Season**	**Wind Speed**	**Wind Direction**
Spring	6.5 mph (10.5 km/h)	268°	Spring	7.5 mph (12.1 km/h)	268°
Summer	4.3 mph (6.9 km/h)	270°	Summer	6.2 mph (9.9 km/h)	271°
Autumn	4.8 mph (7.7 km/h)	275°	Autumn	6.6 mph (10.6 km/h)	276°
Winter	6.7 mph (10.8 km/h)	275°	Winter	8.4 mph (13.5 km/h)	262°
Annual	5.5 mph (8.9 km/h)	267°	Annual	7.2 mph (11.6 km/h)	267°

Table 2.4: Meteorological Averages by Season for the Year 2012

Season	Wind Speed	Wind Direction	Air Temp	Pressure	Relative Humidity	Precipitation
Spring	7.5 mph (12.1 km/h)	268°	60.5°F (15.8°C)	1016 mb	70.6%	Rain
Summer	6.2 mph (9.9 km/h)	271°	72.7°F (22.6°C)	1015 mb	75.8%	Light Rain
Autumn	6.6 mph (10.6 km/h)	276°	54.5°F (12.5°C)	1018 mb	76.7%	Rain
Winter	8.4 mph (13.5 km/h)	262°	41.7°F (5.4°C)	1018 mb	76.9%	Light Snow
Yearly	7.2 mph (11.6 km/h)	267°	57.4°F (6.7°C)	1017 mb	74.9%	Rain

The spring UF_6 plume reached a peak maximum temperature of 168°F (76°C) at a distance of 31 meters from the release point (Figure 2.2). The plume temperature then decreased after the plume extended beyond 31 meters with the temperature falling to 136°F (58°C) at 65 meters from the release point (Figure 2.2). The plume height ascended rapidly between 30 and 65 meters from the release point from a height of 5 meters to a height of 52 meters at a distance of 65 meters (Figure 2.3). According to the model, all UF_6 reacted with moisture at a distance of 64.4 meters from the release point.

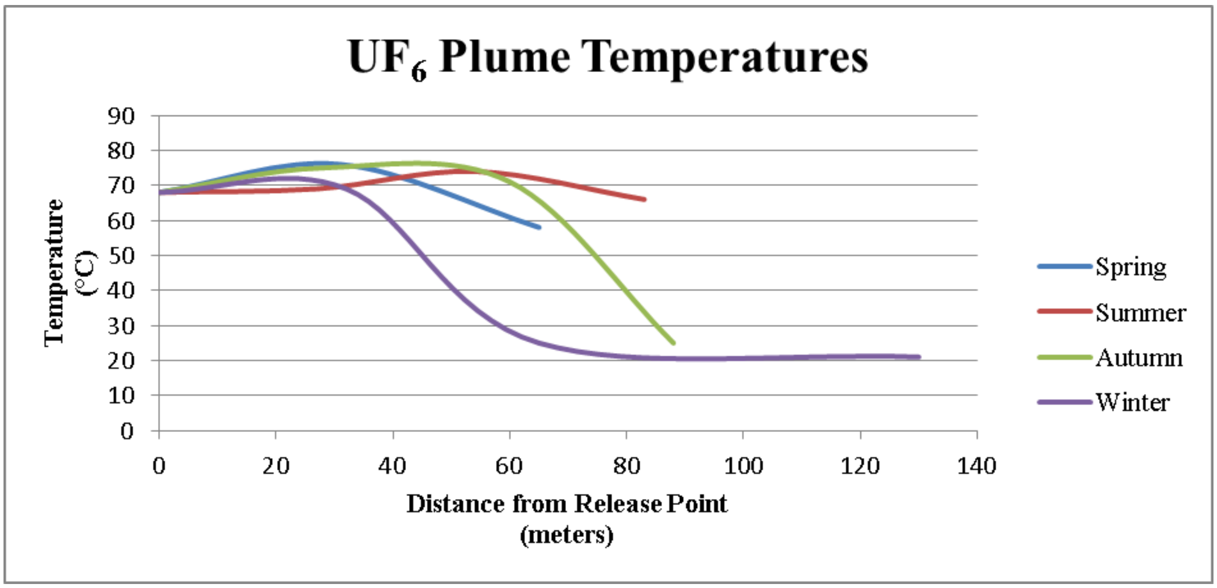


Figure 2.2: UF_6 Plume Temperatures for All Seasons

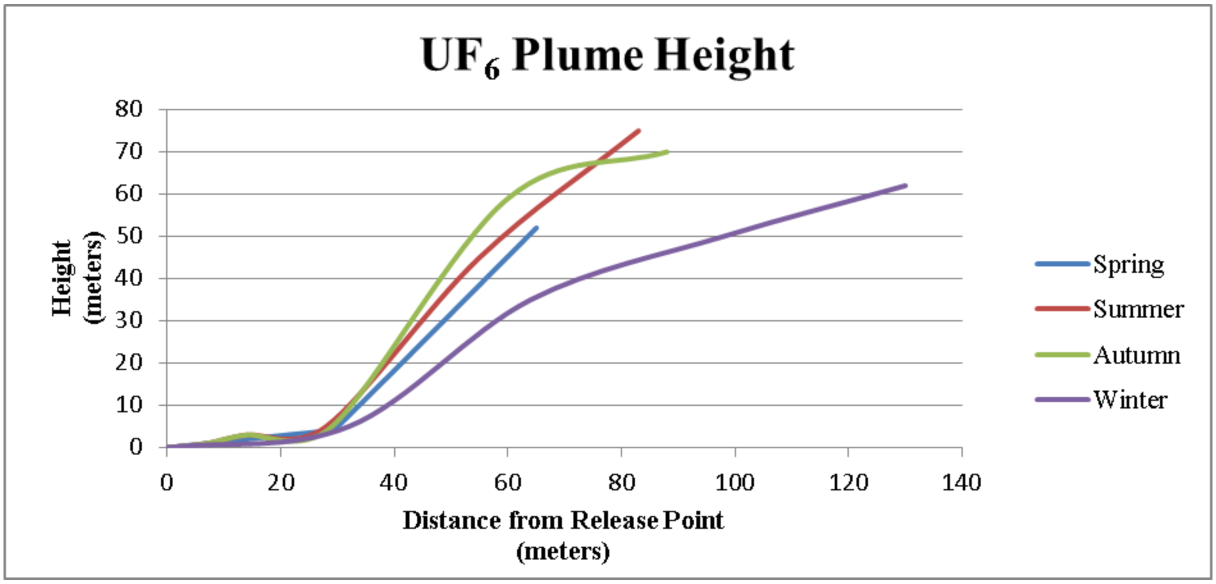


Figure 2.3: UF_6 Plume Heights for All Seasons

The summer UF_6 plume reached a peak maximum temperature of 165°F (74°C) at a distance of 27 meters from the release point (Figure 2.2). The plume temperature then decreased after the plume traveled beyond 54 meters with the temperature falling to 150°F (66°C) at 83 meters from the release point (Figure 2.2). The plume height ascended rapidly between 28 and 83 meters from the release point from a height of 5 meters to a height of 75 meters at a distance of 83 meters from the release point (Figure 2.3). According to the model, all UF_6 reacted with moisture at a distance of 82.9 meters from the release point.

The autumn UF_6 plume reached a peak maximum temperature of 167°F (75°C) at a distance of 28 meters from the release point (Figure 2.2). The plume temperature remained consistently high until the plume reached a distance of 60 meters when the temperature dropped from 159°F (71°C) to 77°F (25°C) at a distance of 88 meters (Figure 2.2). The plume height ascended rapidly from a height of 5 meters to 59 meters at a distance of 60 meters from the release point and then increased gradually to a height of 70 meters at a distance of 88 meters from the release point (Figure 2.3). Per the model, all UF_6 reacted with moisture at a distance of 88.1 meters from the release point.

The winter UF_6 plume reached a peak maximum temperature of 156°F (69°C) at a distance of 32 meters from the release point (Figure 2.2). The plume temperature was consistent from the release point to 32 meters when the temperature dropped drastically to 77°F (25°C) at a distance of 65 meters from the release point and then decreased gradually to a temperature of 69°F (21°C) at a distance of 130 meters from the release point (Figure 2.2). The plume height ascended drastically from a height of 5 meters at a distance of 32 meters from the release point to a height of 62 meters at a distance of 130 meters from the release point (Figure 2.3). Per the model, all UF_6 reacted with moisture at a distance of 128.7 meters from the release point.

HF concentration plume models for all seasons and tank sizes ranged from 0.001 ppm to 50 ppm with health effects ranging from no adverse health effects to life threatening health effects (Figure 2.4 and Appendix B). HF deposition plume models for all seasons and tanks sizes ranged from 0.001 g/m^2 to 1 g/m^2 (Figure 2.4 and Appendix B). U concentration plume models for all seasons and tank sizes fell below the Environmental Protection Agency's (EPA) Protection Action Guides (PAG) range in the 0.001 to 1 rem range (Figure 2.4 and Appendix B). U deposition plume models for all seasons and tank sizes ranged from 0.01 g/m^2 to 100 g/m^2 (Figure 2.4 and Appendix B).

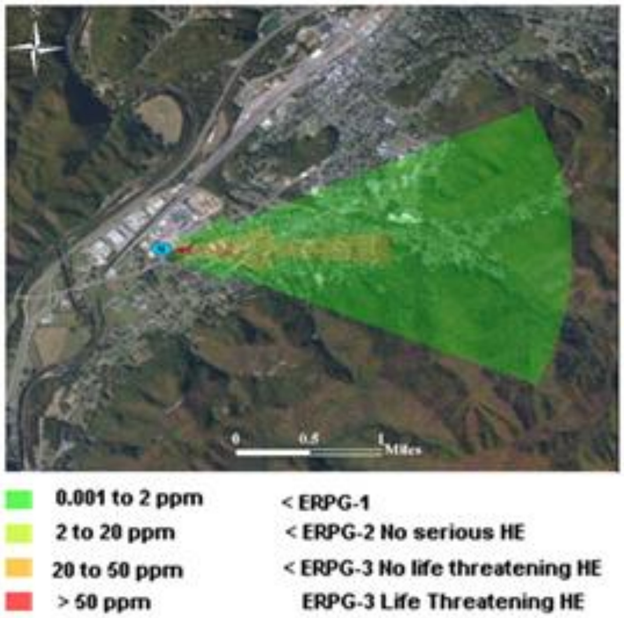


Figure A: HF concentration plume for a 14 ton cylinder using meteorological averages for the year 2012.

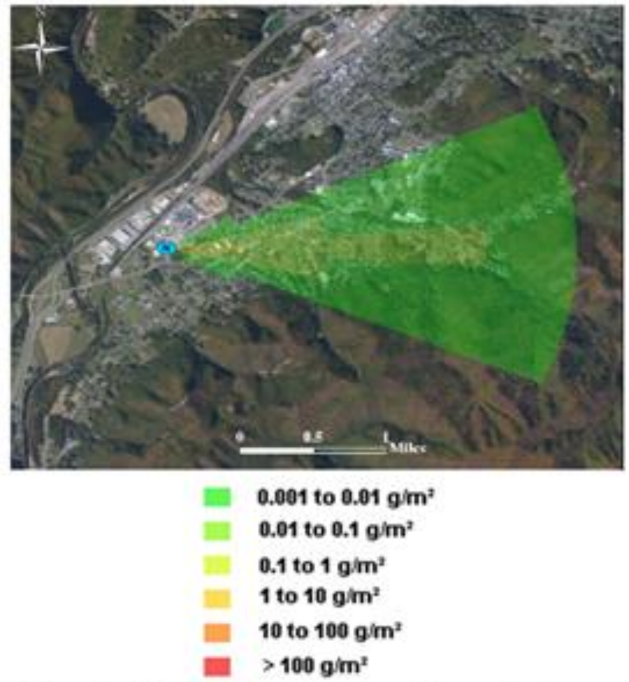


Figure B: HF deposition plume for a 14 ton cylinder using meteorological averages for the year 2012.

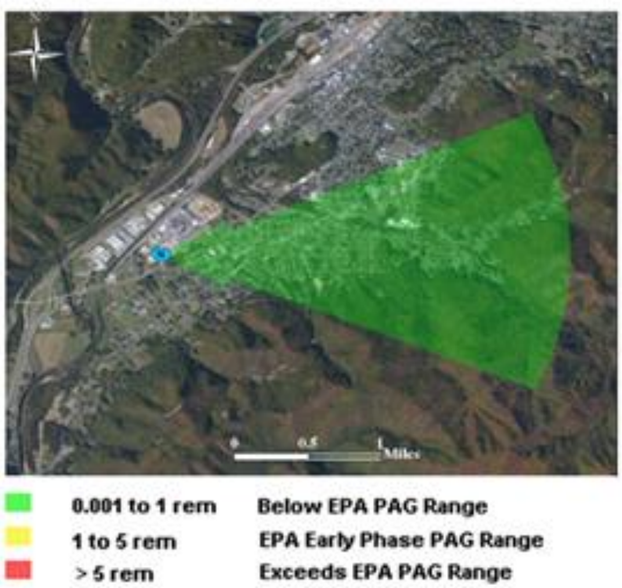


Figure C: Uranium concentration plume for a 14 ton cylinder using meteorological averages for the year 2012.

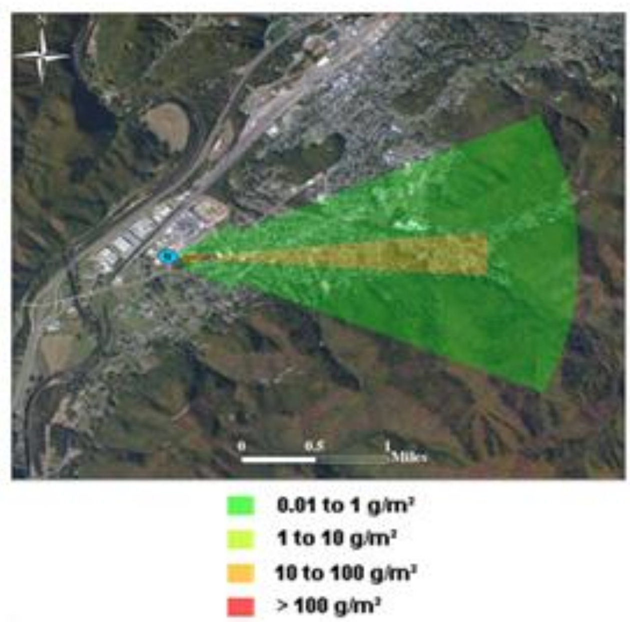


Figure D: Uranium deposition plume for a 14 ton cylinder using meteorological averages for the year 2012.

Figure 2.4: HF and Uranium Concentration and Deposition Plume Models. Models are based on a 14 ton cylinder using meteorological averages for the year 2012.

Based on past UF_6 incidents it is determined that the possibility of a cylinder rupture occurring is low and if a cylinder rupture did occur the impact to the adjacent community would be minor (Table 2.5). Table 2.5 identifies expected impacts for ruptures of cylinders of varying size.

Table 2.5: Risk Assessment Matrix for Erwin, Tennessee

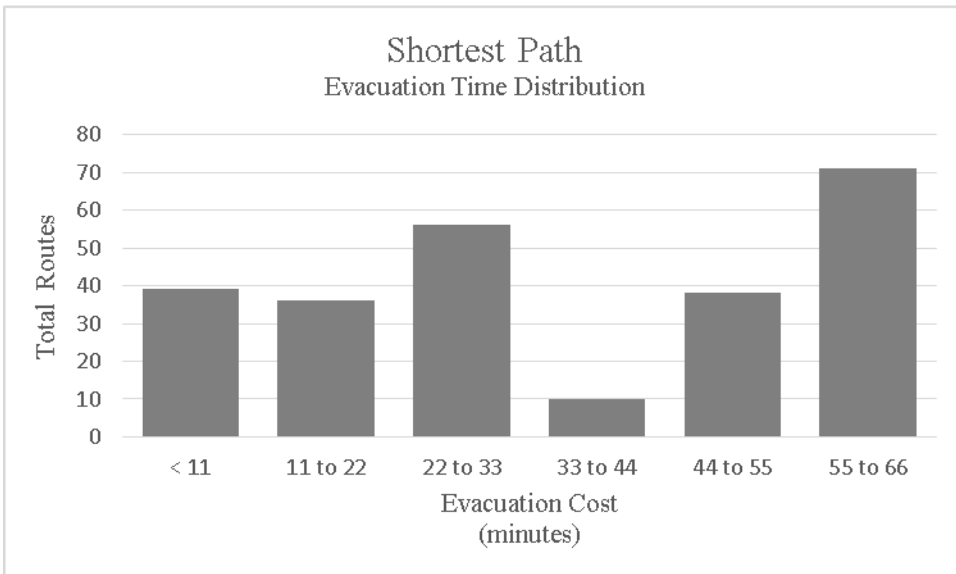
Cylinder Rupture Risk Assessment				
Impact	**2.5 Ton Cylinder**	**10 Ton Cylinder**	**14 Ton Cylinder**	**Multiple Tank Ruptures**
Catastrophic	**Very Low**	**Very Low**	**Very Low**	**Very Low**
Major	**Very Low**	**Very Low**	**Very Low**	**Very Low**
Moderate	**Very Low**	**Very Low**	**Very Low**	**Very Low**
Minor	**Low**	**Low**	**Low**	**Very Low**
Insignificant	**Low**	**Low**	**Low**	**Very Low**

3.2 Scenario 1 Results

Scenario number one allowed for the use of the entire road network (i.e., state maintained roads) for evacuation purposes. The shortest path algorithm resulted in the evacuation of the EPZ in 66 minutes (Table 2.6). The majority of the evacuation routes were in the high range of

55 to 66 minutes (i.e., it "cost" an evacuee 55-66 minutes of time to evacuate to the nearest safe zone) with less than a quarter of all evacuation routes in the < 11 minute range (Table 2.6). The 55 to 66 minute evacuation routes centered in the downtown area of Erwin (Figure 2.5). The major road arteries affected by congestion were Ohio Avenue, Carolina Avenue, North Main Avenue and Love Street (Figure 2.1 and 2.5).

Table 2.6: Scenario 1 Shortest Path Algorithm Evacuation Time Distribution



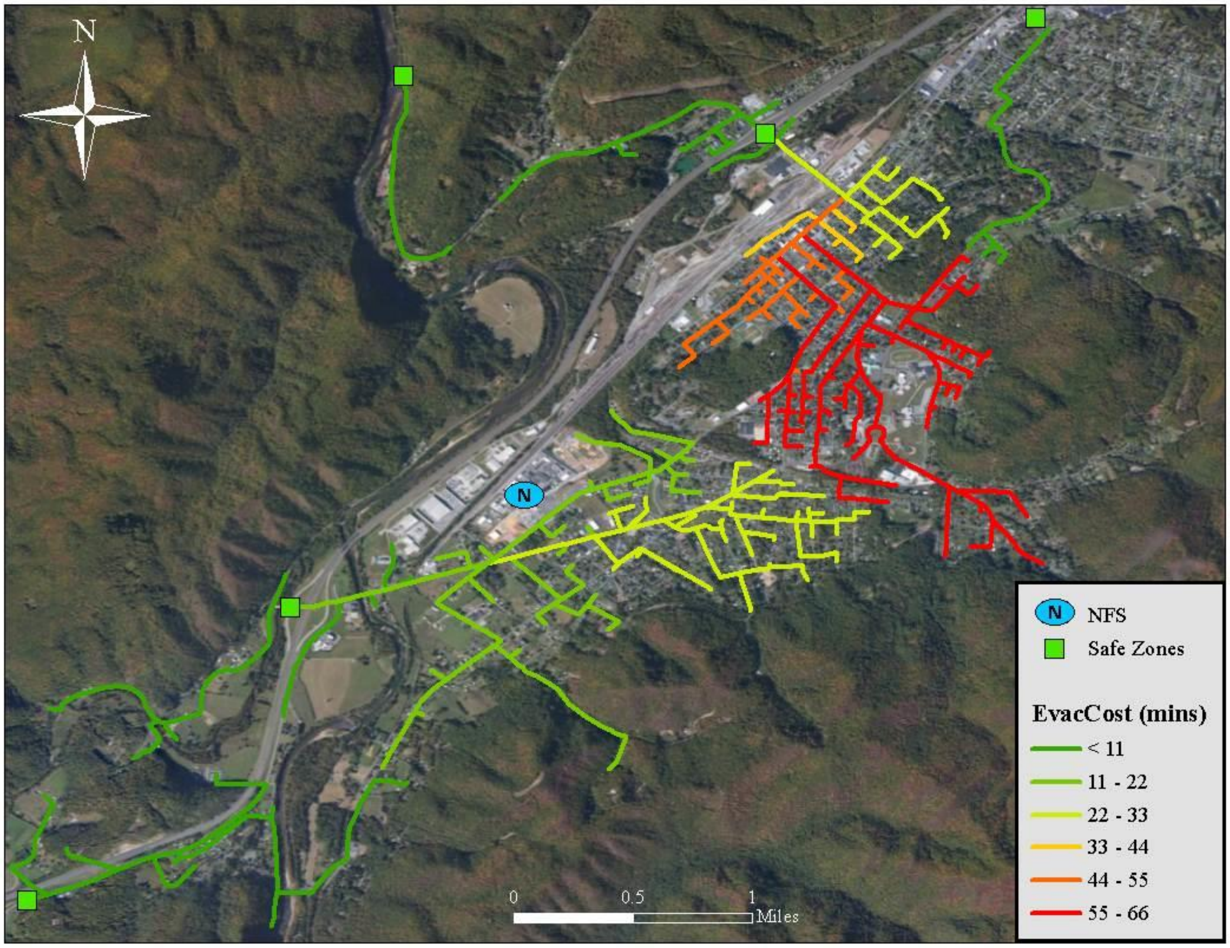
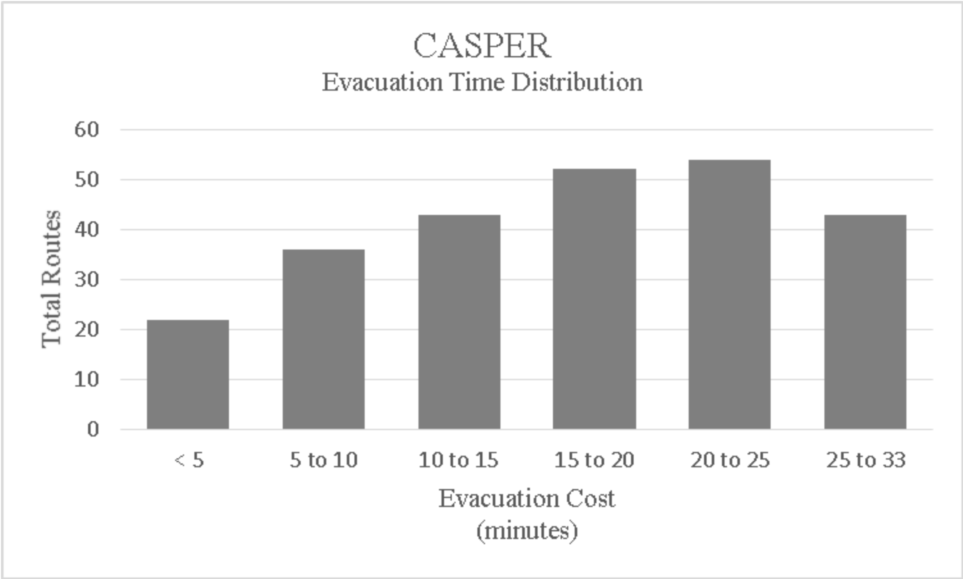


Figure 2.5: Scenario 1 Evacuation Model Using the Shortest Path Algorithm

The CASPER algorithm resulted in the evacuation of the EPZ in 33 minutes (Table 2.7). The majority of the evacuation routes ranged between 20 to 25 minutes which accounted for approximately 20% of the total evacuation population (Table 2.7). Congestion points ranged in the 25 to 33 minute range (Table 2.7). The major arterial roads affected by congestion were located in the southern portion of the EPZ (Figure 2.6) and included Chestoa Pike, Jackson Love Highway, and Carolina Avenue (Figure 2.1 and 2.6).

Table 2.7: Scenario 1 CASPER Algorithm Evacuation Time Distribution



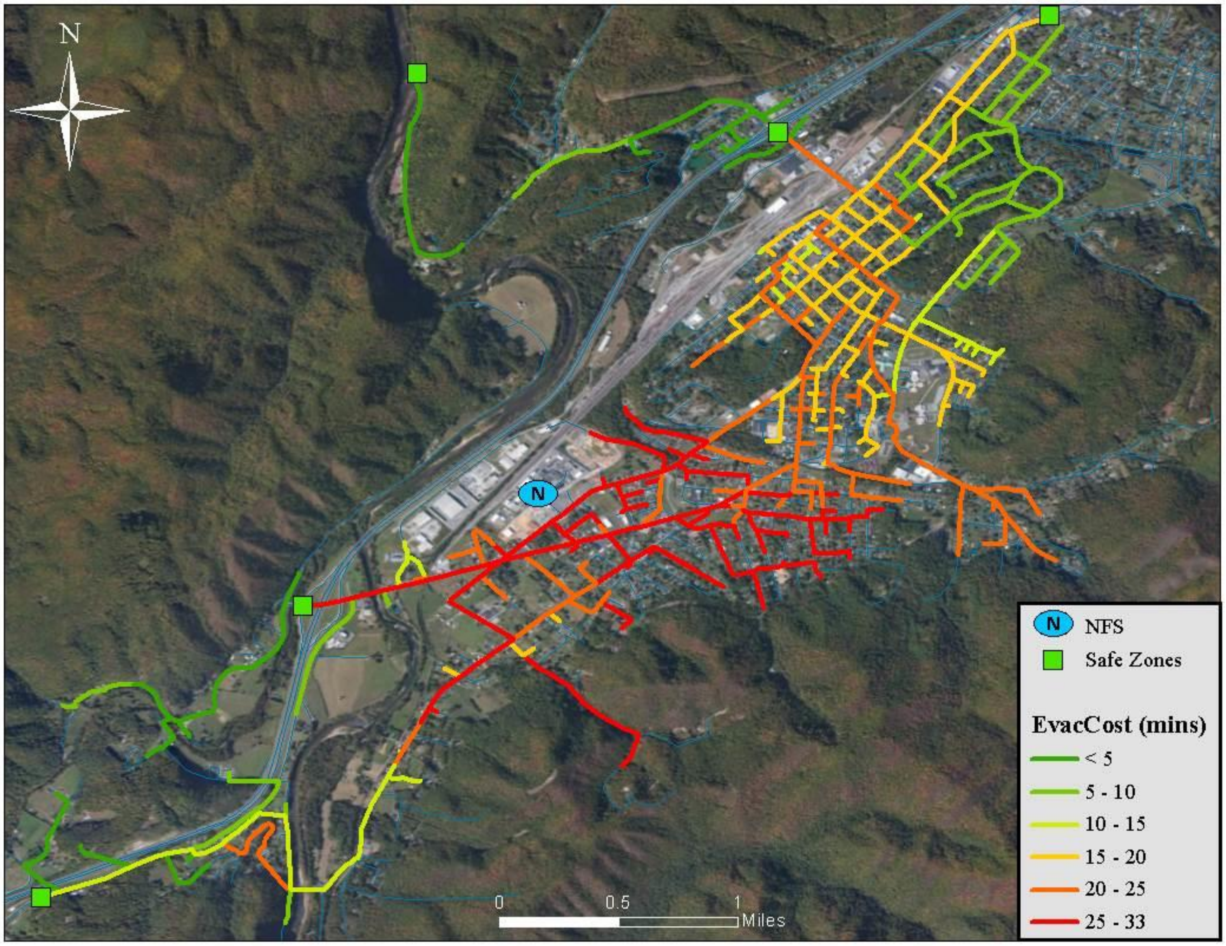
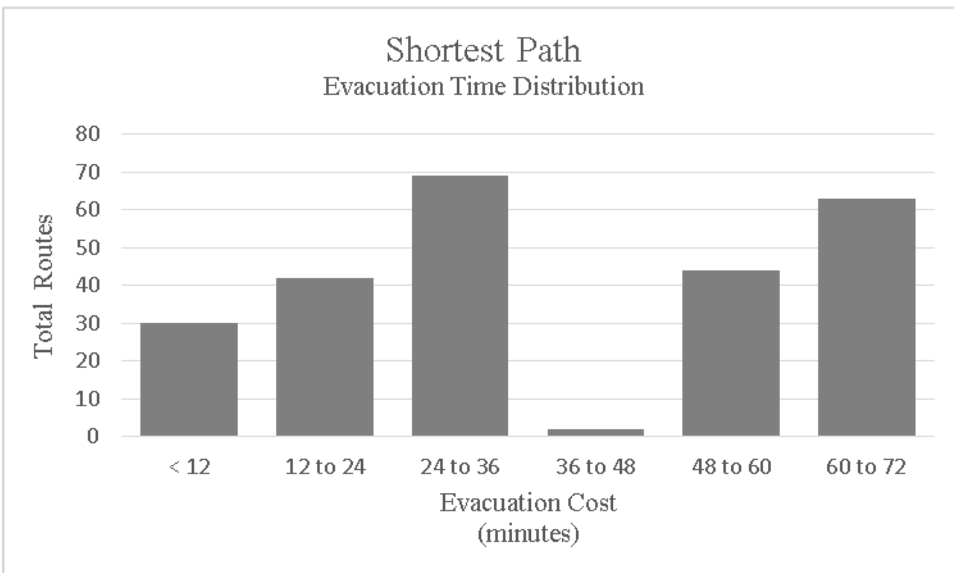


Figure 2.6: Scenario 1 Evacuation Model Using the CASPER Algorithm

3.3 Scenario 2 Results

Scenario number two simulated a train restricting the movement of cars on a segment of Tennessee 107, so a portion of the road was unavailable within the evacuation model. The shortest path algorithm for scenario two resulted in the evacuation of the EPZ in 72 minutes (Table 2.8). The majority of the evacuation routes were 24 to 36 minute range followed by the 60 to 72 minute range (Table 2.8). Congestion was centered in the southeast section of Erwin affecting the major roadways of Ohio Avenue and Jackson Love Highway (Figure 2.1 and 2.7).

Table 2.8: Scenario 2 Shortest Path Algorithm Evacuation Time Distribution



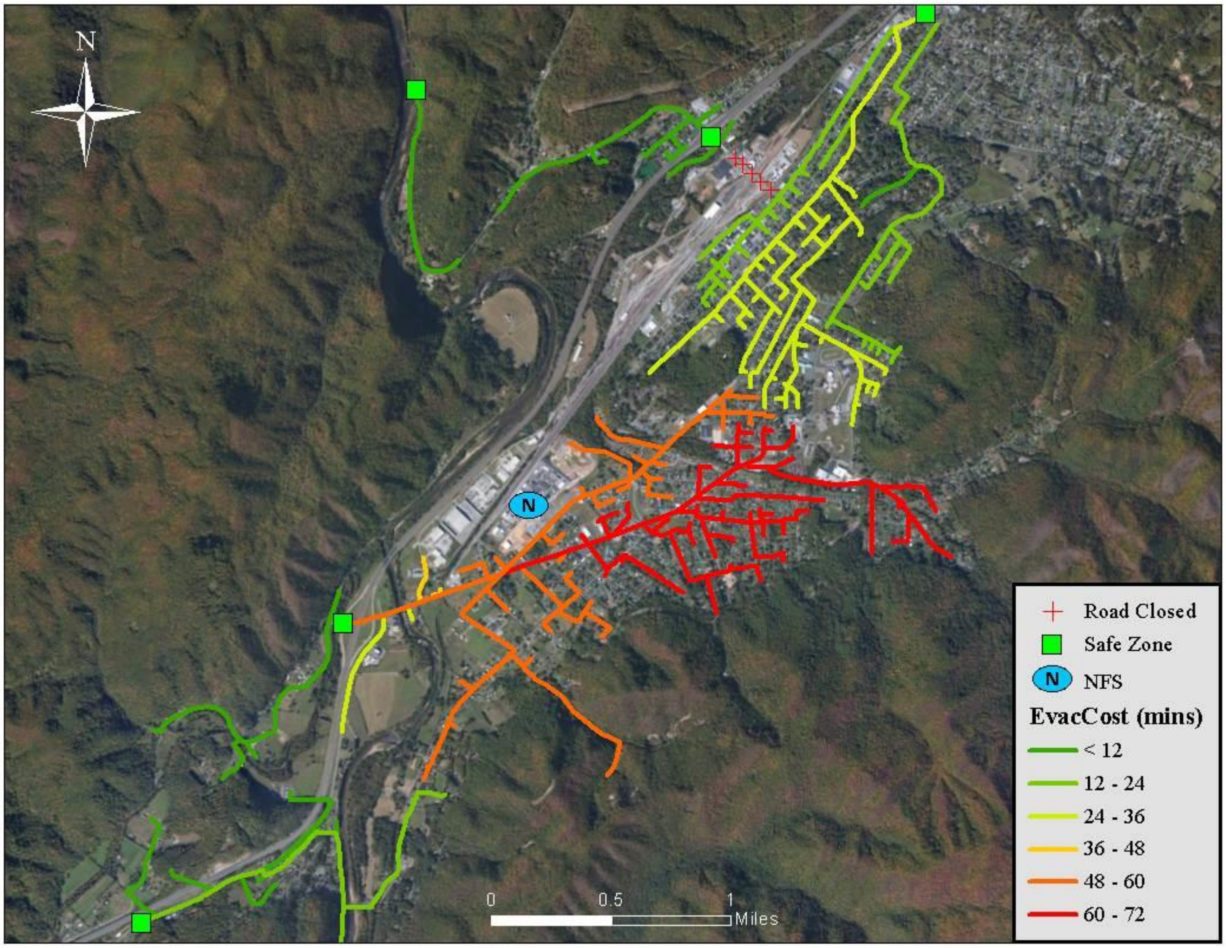
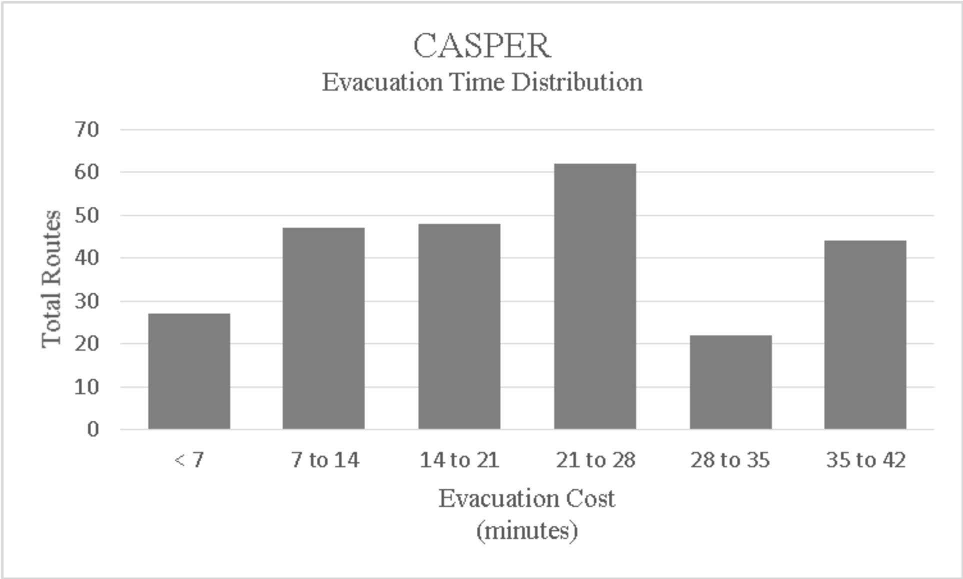


Figure 2.7: Scenario 2 Evacuation Model Using the Shortest Path Algorithm. The red crosses in top center of figure indicate road closer due to trains blocking the roadway. An overpass bridge is located approximately 2 miles north and an underpass bridge is located approximately 3 miles south of this point.

The CASPER algorithm for scenario number 2 resulted in the evacuation of the entire EPZ in 42 minutes (Table 2.9). The majority of the evacuation routes ranged between 21 to 28 minutes (Table 2.9). Congestion points for the CASPER algorithm for scenario 2 were located in the downtown area and in south Erwin (Figure 2.8). The congested roads in the downtown area were secondary roads. Primary roads in the southern section that were affected by congestion were Carolina Avenue, portions of Jackson Love Highway, and portions of Ohio Avenue (Figure 2.1 and 2.8).

Table 2.9: Scenario 2 CASPER Algorithm Evacuation Time Distribution



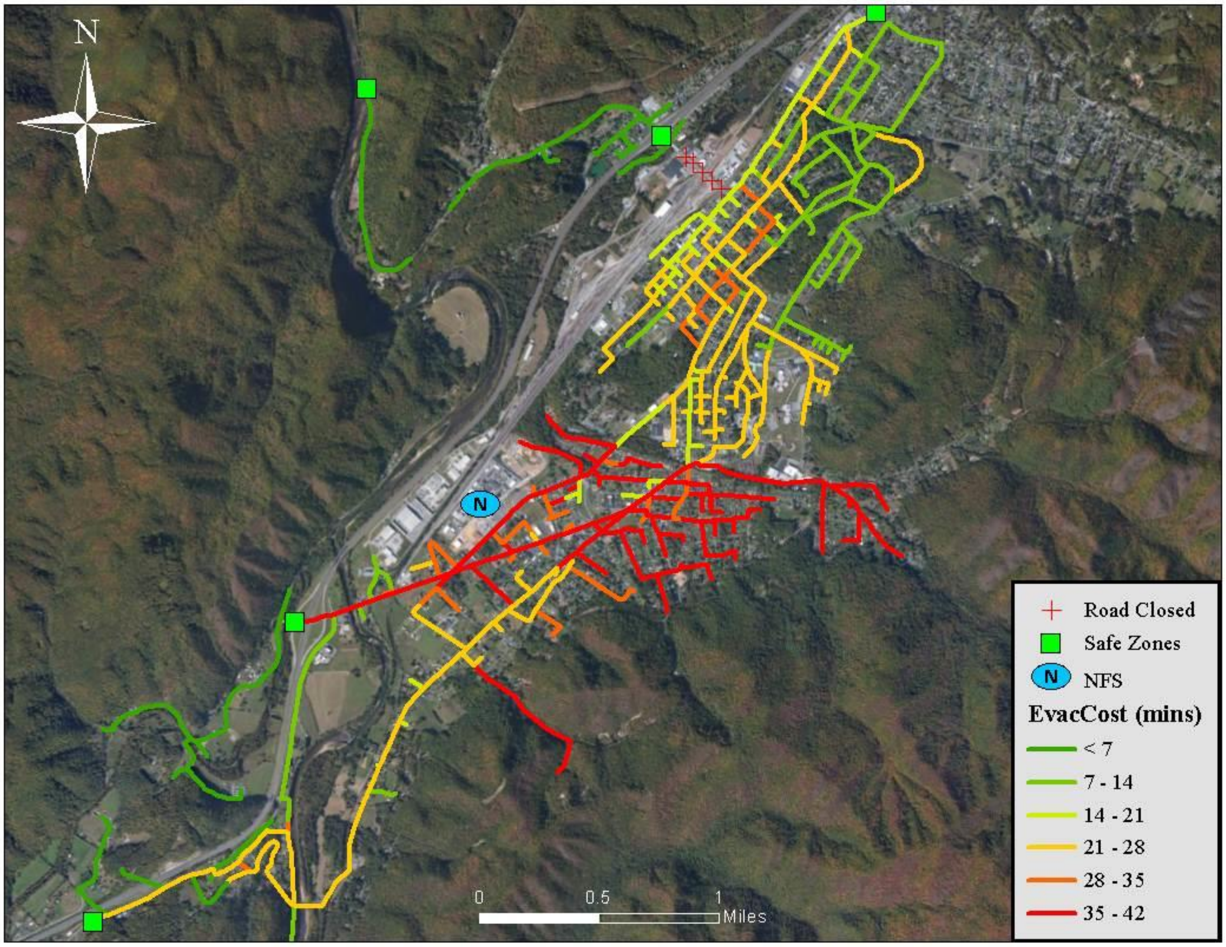


Figure 2.8: Scenario 2 Evacuation Model Using the CASPER Algorithm

4. Discussion and Conclusions

Wind speed has a direct influence on a chemical plume's dispersion across an area. Wind speed for the year 2012 was higher than the 30 year average which resulted in the chemical plume traveling further from the chemical release point due to an increase in velocity, but also reduced the width of the plume per the model. In contrast, lower wind speeds decreased the dispersal distance of the plume from the release point, but increased the width of the plume.

U deposition is dependent upon meteorological conditions and mas released, with stronger winds and larger tank sizes (filled to capacity) creating a higher level of U deposition across a larger area. Despite this, the models demonstrate that the levels of U concentration remain below the EPA PAG range and are not an immediate health hazard. Similar results were found for HF deposition, but HF concentration could be significant enough to cause life threatening health effects as mass increases. A 2.5 ton cylinder filled to capacity in any season has the potential to cause severe health effects, but an increase to a 10 ton cylinder filled to capacity introduces the possibility of life threatening health effects. The 14 ton cylinder life threatening zone stays consistent with the 10 ton cylinder results, but the severe health effects zone extends farther from the release site. The yearly averages along with the 14 ton cylinder specifications allowed for the evaluation of evacuation and shelter in place actions that can be implemented in the early stages of a UF_6 release for any season.

Sheltering in place is suggested in both scenarios for all critical facilities in the direct path of the UF_6 plume. Evacuation of large populations from critical facilities such as schools, hospitals and nursing homes takes considerable time, which increases an individual's exposure to a hazardous cloud. This increase in exposure time also increases the odds of an individual to experience life-threatening health effects. This strategy is also recommended for citizens who lack the means to evacuate due to a lack of transportation, poor health or age, and for those outside of the two mile buffer zone.

The CASPER evacuation algorithm was determined to be the most effective method of modeling evacuation routes. In both scenarios, CASPER outperformed the shortest path algorithm in the total time it takes to evacuate the EPZ. It was determined in scenario number two that a train blocking Tennessee Highway 107 would increase the total time it takes to evacuate the EPZ in the CASPER model by 9 minutes and by 6 minutes in the shortest path. In both scenarios, the major road ways of Carolina Avenue, Jackson Love Highway, and Ohio Avenue experienced the most congestion. These areas are very close to the release point, but the evacuation times are short enough to reduce the exposure to UF_6 so an evacuation is still suggested for those residents over a shelter in place action if the evacuation order is given directly after the release occurs.

References

[1] S.A. McGuire, Chemical toxicity of uranium hexafluoride compared to acute health effects of radiation, US NRC. (1991). NUREG-1391.

[2] K.M. Thiessen, D.E. Weil, J. Morris, J. Drury, F. Smith, Summary review of health effects associated with hydrogen fluoride and related compounds, US EPA. (1988) EPA/600/8-89/002F.

[3] M. Salama, Emergency preparedness and response in case of a fire accident with UF_6 packages traversing the Suez Canal, Packaging, Transport, Storage, and Security of Radioact. Mater. 15 (2004) 253-256.

[4] J.M. Hans, T.G. Sell, Evacuation risks – an evaluation, US EPA. (1974). EPA-520/6-74-002.

[5] P.S. Georgiado, I.A. Papazoglu, C.T. Kiranoudis, N.C. Markatos, Modeling emergency evacuation for major hazards and industrial sites, Reliab., Eng., and Syst, Saf. (2007) 1388-1402.

[6] W.R. Chan, W.W. Nazaroff, P.N. Price, A.J. Gadgil, Effectiveness of urban shelter-in-place II: Residential districts, Int. J. of Geogr. Inf. Sci. (2007) 763-784.

[7] Environmental Systems Research Institute, What is GIS?, Overview. (2014) [Internet]. www.esri.com/what-is-gis/overview.

[8] J.W. Cole, C.E. Sabel, E. Blumenthal, K. Finnis, A. Dantas, S. Barnard, D.M. Johnson, GIS-based emergency and evacuation planning for volcanic hazards in New Zealand, Bull. Of the New Zealand Soc. for Earthq. Eng. (2005) 149-164.

[9] K. Shabai, Out of harm's way: Enabling intelligent location-based evacuation routing, ArcUser. (2012) [Internet]. www.esri.com/news/arcuser/0612/out-of-harms-way.html.

[10] J.V. Ramsdell Jr, G.F. Athey, S.A. McGuire, L.K. Brandon, RASCAL 4: Description of models and methods, U.S. NRC. (2012) NUREG-1940.

[11] F.R. Spellman, M.L. Stoudt, Nuclear Infrastructure Protection and Homeland Security, Lanham, Maryland, 2011.

CHAPTER 3

DISCUSSION AND MAJOR FINDINGS

The following are all major findings of this study:

1) UF_6 plume models were created based on yearly meteorological conditions for the year 2012 and imported into a GIS. Areas affected by a UF_6 plume were identified and protective measures were recommended.
2) All critical facilities were identified and a shelter in place action was recommended for these facilities due to transportation needs and exposure time.
3) RASCAL 4.3 and ArcCASPER in conjunction with a GIS have demonstrated the usefulness of software in developing an emergency action plan. RASCAL 4.3 allowed for the creation of plume models to identify at risk areas once the plume models were imported into a GIS. The ArcCASPER network analyst tool not only created adequate evacuation routes but provided the option of choosing between 3 separate algorithms that allow the user to compare the results of the 3 methods.
4) Evacuation actions were recommended for the populace within 2 miles of the chemical release point and for those in the direct plume path outside of the 2-mile zone extending up to 5 miles. Shelter in place actions were recommended for all critical facilities within 2 miles of the chemical release point and for the facilities in the direct plume path outside of the 2-mile zone.

Past evacuations have demonstrated that emergency evacuations do not always occur as planned due to the population’s perception of the risk or their inability to evacuate. In the Three Mile Island incident, the governor ordered only pregnant women and preschool children within a 5-mile radius to evacuate, but the majority of the populace ignored this order resulting in the evacuation of a 25 mile radius. In contrast, an evacuation order was issued to the citizens of New Orleans during Hurricane Katrina, but a substantial amount of the populace refused to evacuate or did not have the ability to evacuate. These incidents highlight the need to increase predisaster education efforts that are focused on increasing people's timely compliance with evacuation and sheltering orders.

Study Limitations

There were limitations within this study pertaining to available data. The availability of a reliable road network for GIS analysis was one of the early challenges. Many of the digitized roads within the available road networks did not match the base maps available in ESRI's ArcMap 10.0. One of these datasets was the US Census Bureau's Topologically Integrated Geographic Encoding and Referencing (TIGER) road dataset. This dataset contained several discrepancies that made the data ineffective in creating a network dataset. These discrepancies involved the absence of some roads within Unicoi County, the addition of roads that do not physically exist, and a misrepresentation of some road segments (e.g. wrong location, wrong length, missing segments). To counter these problems, the road network of Unicoi County was digitized from satellite imagery to ensure accuracy of the road network and improve the reliability of model results.

Another problem encountered during this study was the lack of a weather station with accurate and reliable data in Erwin, Tennessee. The nearest reliable weather station was situated approximately 50 miles away in Blountville, Tennessee. Erwin is located within a valley that may experience mountain-valley breezes that impact wind speed, wind direction and temperatures. A reliable weather station in this area would greatly enhance future studies that require meteorological data from the area.

The lack of information available from NFS was another limitation faced throughout this study. Several attempts were made to include NFS in the study, but due to the sensitivity of the subject matter, knowledge of currently stored chemicals, and other variables were unknown. Because of this, several assumptions were made involving key components of the study.

Assumptions

Due to the lack of information available from NFS, several assumptions had to be made during the course of this study:

1) UF_6 cylinders have been present on the NFS site in the past, but it could not be confirmed if they are currently being used and stored on site at this time.
2) The cylinder inventory list included within the RASCAL 4.3 software program was used to determine tank size and volume because it is unknown what size tanks have been in use at the NFS facility.
3) It was assumed that UF_6 was in a liquid state when modeling chemical release plumes using RASCAL 4.3. The release rate, release fraction, and uranium enrichment level variables for liquid UF_6 were obtained from the default values within the RASCAL 4.3 software program.
4) A direct release to the atmosphere with no reductions (e.g. through a building, through filters) was used for each chemical plume model because it is not known where on site UF_6 cylinders have been stored.

Future Research

Erwin faces transportation problems as it relates to road infrastructure and the rail system. Currently, there are 3 major access points that allow for vehicles to cross the rail system that runs directly through town. Two of these points are either underpass or overpass bridges that permit the flow of vehicular traffic even if a train is present on the tracks, but the access point in the downtown area cannot be crossed if a train is present. A proposal to build a bridge in this area is currently in the developmental phase and it would benefit the community if research on evacuation modeling was conducted in the future to determine the effectiveness of this bridge in facilitating evacuation.

Several other avenues for future research exist, including the study of mass evacuations during specific times of the day and on specific days of the year, such as the popular Apple Festival, which draws approximately 110,000 people annually to the city center in late Autumn. Furthermore, the local population will increase in residential areas during the night time hours and increase in commercial areas during the day. This diurnal shift in population distribution will impact the time required for evacuation in residential versus commercial areas as a function of the time of day. Further studies should target sheltering in place and how the safety of doing so is affected by infiltration rates of chemicals in certain buildings. Certain structures may be more susceptible to certain chemicals rendering a shelter in place action useless.

Improved evacuation models can be created by performing a risk assessment of the community by using socio-demographic data. Cutter *et al.* (2000) developed a method for assessing vulnerability by evaluating social characteristics such as population, differential access to resources, and level of wealth. This type of research can enhance the evacuation model by identifying the segment of the population that may be unable to evacuate due to financial means, age, health, and gender.

Another area for future research is the evaluation of other anthropogenic and natural hazards that may affect the populace. This study only examined the chemical release of UF_6 from Nuclear Fuel Services, but it is possible that a different chemical may increase the population's risk if it was released. Nuclear Fuel Services also ships and receives numerous amounts of chemicals by rail through the town of Erwin, which could pose a threat to the community in the event of a train incident. Future research is necessary to understand the risks associated with railway hazards. As far as natural hazards are concerned, Erwin's geographical location makes it very susceptible to flooding, which has been a major concern in the past. Identifying the areas at risk and implementing an evacuation action for these areas would be beneficial to the community and aid in mitigating potential injury and loss of life.

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

RASCAL 4.3 and ArcCASPER in conjunction with a GIS have demonstrated the usefulness of geospatial modeling software to create an emergency evacuation and sheltering plan for a specific chemical release at NFS. The functions provided within these software programs were efficient and allowed for an evaluation of the possible affected areas. These software were valuable tools throughout the research process.

Mandatory evacuation and sheltering in place used in combination with each other were determined to be effective strategies in the event of a UF_6 chemical release. The infrastructure in Erwin is sufficient to accommodate an efficient and timely evacuation of the populace within 2 miles of the chemical release and downwind of the projected chemical plume; however, all critical facilities located in the chemical plume path were recommended to shelter in place because efficient and effective evacuation of these facilities is improbable. This increases the exposure time to the UF_6 chemical.

This study has demonstrated that the potential for a cylinder rupture is low, and that the impact of a cylinder rupture is minor due to the dissipation of the UF_6 chemical before it reaches a large populace. However, it is imperative that the populace remain vigilant for industrial hazards as history has demonstrated that complacency can lead to a false sense of security. A hazard can manifest into a disaster when least expected, so it is imperative to develop emergency protocols during the emergency preparedness phase to mitigate injuries and loss of life.

REFERENCES

Bertazzi PA, Bernucci I, Brambilla G, Consonni D, Pesatori AC. 1998. The Seveso studies on early and long-term effects of dioxin exposure: a review. *Environmental Health Perspectives* 106(Supplemental 2):625-633.

Bowonder B. 1985. The Bhopal incident: Implications for developing countries. *Environmentalist* 5(2):89-103.

Chan WR, Nazaroff WW, Price PN, Gadgil AJ. 2007. Effectiveness of urban shelter-in-place II: Residential districts. *International Journal of Geographical Information Science* 11(8):763-784.

Cole JW, Sabel CE, Blumenthal E, Finnis K, Dantas A, Barnard S, Johnston DM. 2005. GIS-based emergency and evacuation planning for volcanic hazards in New Zealand. *Bulletin of the New Zealand Society for Earthquake Engineering* 38(3):149-64.

Collins HE, Galpin F. 1978. Planning basis for the development of state and local government radiological emergency response plans in support of light water nuclear power plants. Washington (DC): US Nuclear Regulatory Commission and US Environmental Protect Agency. General Technical Report No. NUREG-0396 and EPA 520/1-78-016.

Cutter SL, Mitchell JT, Scott MS. 2000. Revealing the vulnerability of people and places: A case study of Georgetown County, South Carolina. *Annals of the Association of American Geographers* 90(4):713-737.

Department of Energy (US). 2000. Independent investigation of the Portsmouth Gaseous Diffusion Plant Volume 1: Past environment, safety and health practices.

Dhara VR, Dhara R. 2002. The Union Carbide disaster in Bhopal: A review of health effects. *Archives of Environmental Health: An International Journal* 57(5):391-404.

Elder K, Xirasagar S, Miller N, Bowen SA, Glover S, Piper C. 2007. African Americans' decisions not to evacuate New Orleans before Hurricane Katrina: A qualitative study. *American Journal of Public Health* 97(Supplemental 1):S124-S129.

ESRI. 2014. What is GIS?, Overview. Environmental System Research Institute. www.esri.com/what-is-gis/overview.

FEMA. 1990. Definitions of Terms. Washington (DC): Federal Emergency Management Agency. Instruction No. 5000.2.

Flynn CB. 1979. Three Mile Island telephone survey: Preliminary report of procedures and findings. Washington (DC): US Nuclear Regulatory Commission.

Garrik BJ. 1988. The approach to risk analysis in three industries: nuclear power, space systems, and chemical process. *Reliability Engineering and System Safety* 23(3):195-205.

Georgiadou PS, Papazoglu IA, Kiranoudis CT, Markatos NC. 2007. Modeling emergency evacuation for major hazards and industrial sites. *Reliability Engineering and System Safety* 92(10):1388-1402.

Hans JM, Sell TG. 1974. Evacuation risks – An evaluation. Las Vegas (NV): US Environmental Protection Agency National Environmental Research Center. General Technical Report No. EPA-520/6-74-002.

Harriss RC, Hohenemser C, Kates RW. 1978. Our hazardous environment. *Environment* 20:7-24.

Jetter JJ, Whitfield C. 2005. Effectiveness of expedient sheltering in place in a residence. *Journal of Hazardous Materials* 188(1-3):31-40.

MacKenzie D. 2002. Fresh evidence on Bhopal disaster. *New Scientist* 19(1).

McGuire SA. 1991. Chemical toxicity of uranium hexafluoride compared to acute effects of radiation. Washington (DC): US Nuclear Regulatory Commission. General Technical Report No. NUREG-1391.

Mitchell JT, Cutter SL, Edmonds AS. 2007. Improving shadow evacuation management: case study of Graniteville, South Carolina chlorine spill. *Journal of Emergency Management* 5(1):28-34.

Podolak EM, Sanders ME. 1988. Criteria for preparation and evaluation of radiological emergency response plans and preparedness in support of nuclear power plants. Washington (DC): US Nuclear Regulatory Commission and Federal Emergency Management Agency. General Technical Report No. NUREG-0654 and FEMA-REP-1.

Quarantelli EL, 1985. What is a disaster? The need for clarification in definition and conceptualization in research. In: Sowder B, editor. Disaster and Mental Health: Selected Contemporary Perspectives. Washington (DC): US Government Printing Office. P. 41-73.

Ramsdell JV, Athey GF, McGuire SA, Brandon LK. 2012. RASCAL 4: Description of models and methods. Washington (DC): US Nuclear Regulatory Commission. General Technical Report No. NUREG-1940.

Salama M. 2004. Emergency preparedness and response in case of a fire accident with UF_6 packages traversing the suez canal. *Packaging, Transport, Storage and Security of Radioactive Material* 15(3-4):253-256.

Shabai K. 2012. Out of harm's way: Enabling intelligent location-based evacuation routing. *ArcUser* [Internet]. Available from: www.esri.com/new/arcuser/0612/out-of-harms-way.html.

Shum E, Cool D, Fairobent J, Swift J, Zalcman B. 1986. Assessment of the public health impact from the accidental release of UF_6 at the Sequoyah Fuels Corporation Facility at Gore, Oklahoma. Washington (DC): US Nuclear Regulatory Commission. General Technical Report No. NUREG-1189 Vol. 2.

Spellman FR, Stoudt ML. 2011. Nuclear Infrastructure Protection and Homeland Security. Lanham (MD): Government Institutes.

Thiessen KM, Weil DE, Morris J, Drury J, Smith F. 1988. Summary review of health effects associated with hydrogen fluoride and related compounds. Research Triangle Park (NC): US Environmental Protection Agency. General Technical Report No. EPA/600/8-89/002F

Urbanik T. 2000. Evacuation time estimates for nuclear power plants. *Journal of Hazardous Materials* 75(2):165-180.

US NRC. 2007. Report to congress on abnormal occurrences: Fiscal year 2006. Washington (DC): US Nuclear Regulatory Commission. General Technical Report No. NUREG-0090 Vol. 29.

US NRC. 2009. Fire in process glove box. Washington (DC): US Nuclear Regulatory Commission. Event Notification No. 45497.

US NRC. 2010. Potentially overpressurized UF_6 cylinders. Washington (DC): US Nuclear Regulatory Commission. Event Notification No. 45642

US NRC. 2012. Report to offsite government agencies and press release due to a chemical spill onsite. Washington (DC): US Nuclear Regulatory Commission. Event Notification No. 47578.

US NRC. 2014. Nuclear Fuel Services. *2.0 Site Status Summary* [Internet]. Available from www.nrc.gov/info-finder/decommissioning/fuel-cycle/nuclear-fuel-services.html

Venart, JES. 2004. Flixborough: the explosion and its aftermath. *Process Safety and Environmental Protection* 82(2):105-127.

Zimmerman LI, Lima R, Pietrobon R, Marcozzi D. 2008. The effects of seasonal variation on hazardous chemical releases. *Journal of Hazardous Materials* 151(1):232-238.

APPENDICES

Appendix A
Meteorological Data for KTRI in Blountville, Tennessee

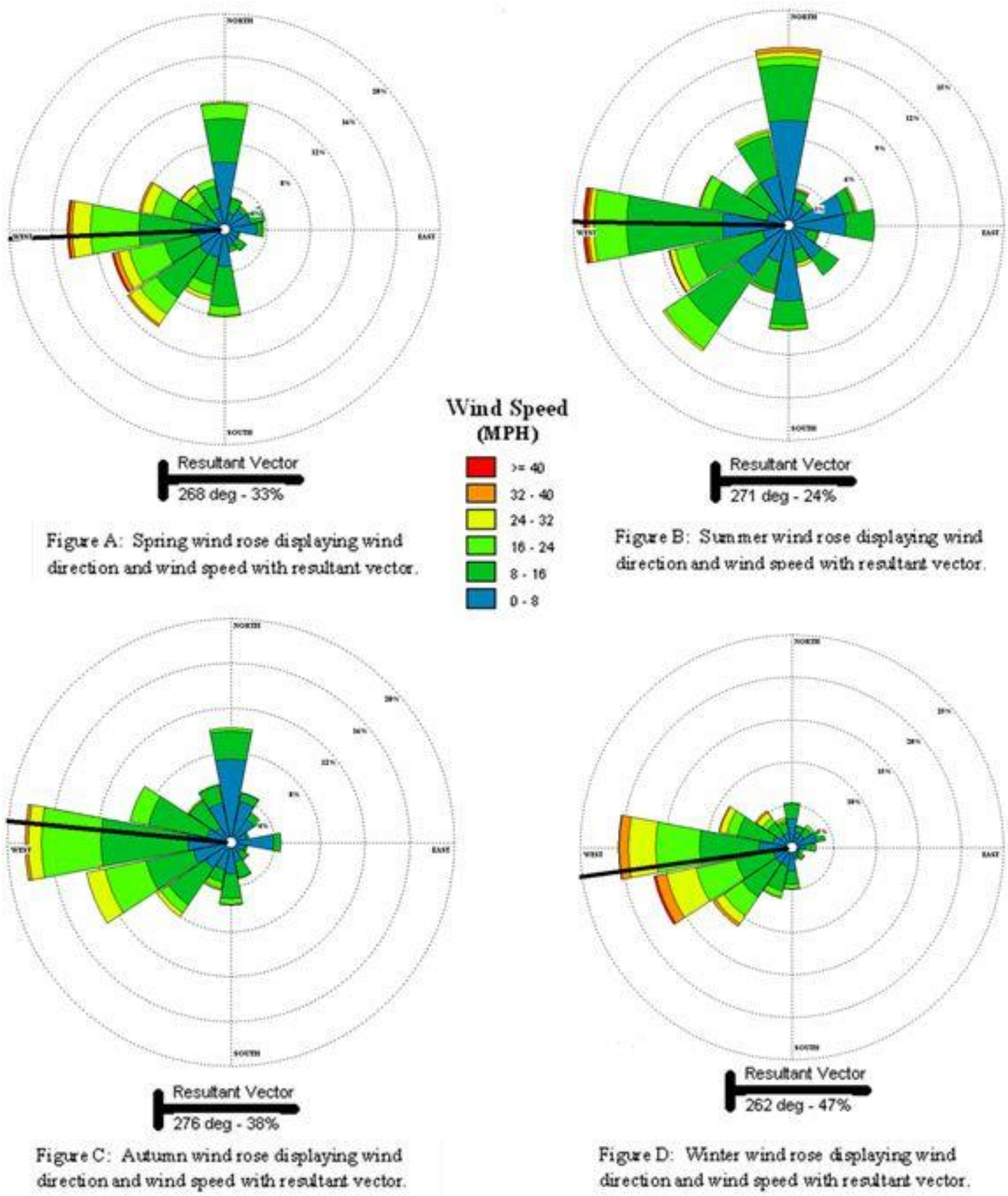


Figure A.1: Seasonal wind speed and direction with resultant vectors for the year 2012.

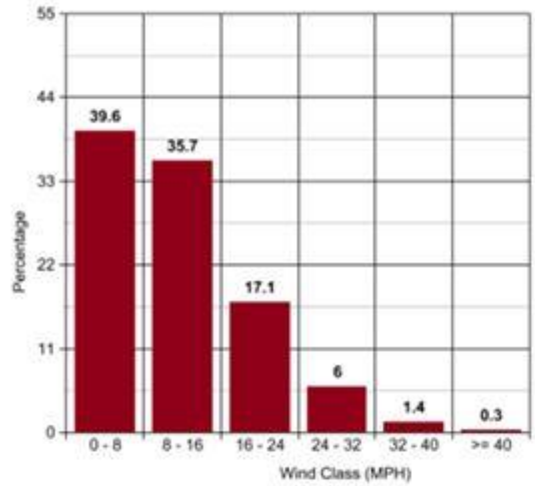


Figure A: Wind speed distribution for the spring of 2012.

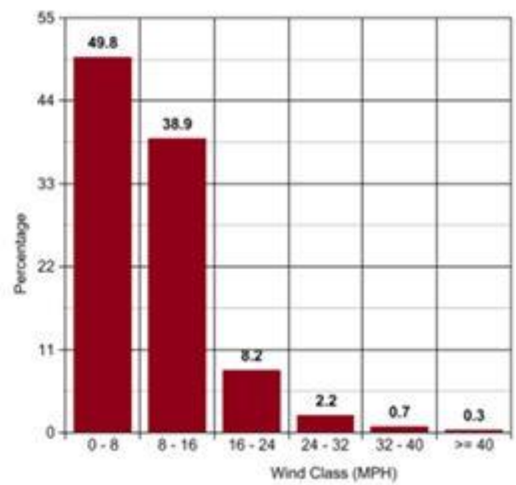


Figure B: Wind speed distribution for the summer of 2012.

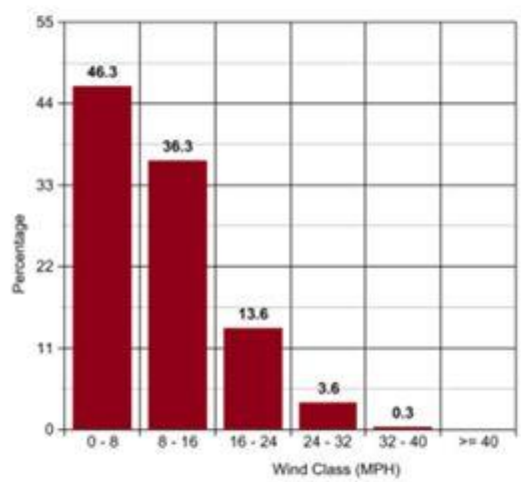


Figure C: Wind speed distribution for the autumn of 2012.

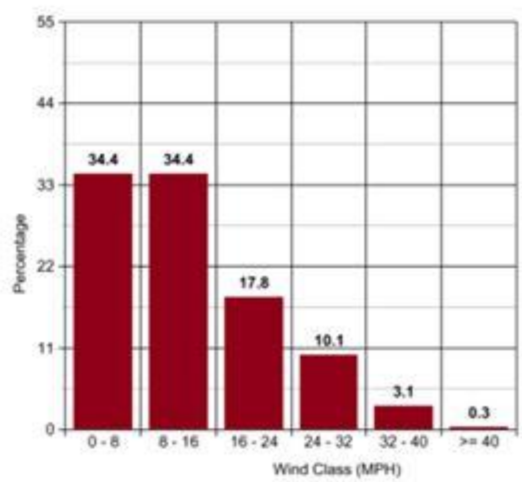


Figure D: Wind speed distribution for the winter of 2012.

Figure A.2: Wind speed distribution by season for the year 2012.

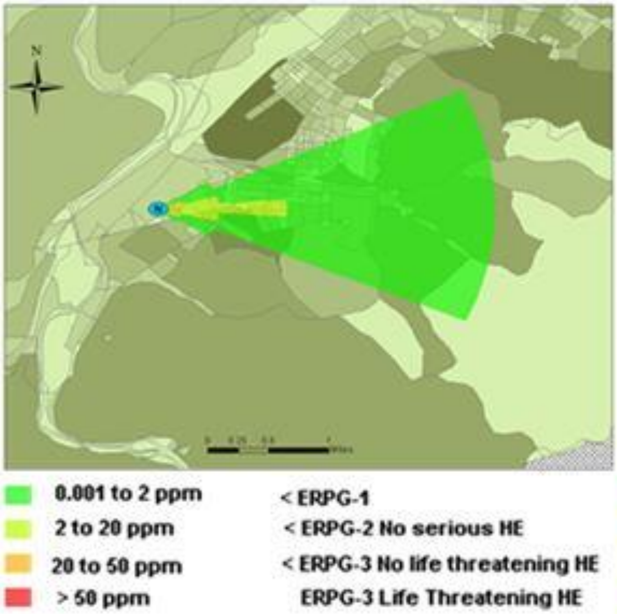


Figure A: HF Concentration plume for a 2.5 ton cylinder for the spring season

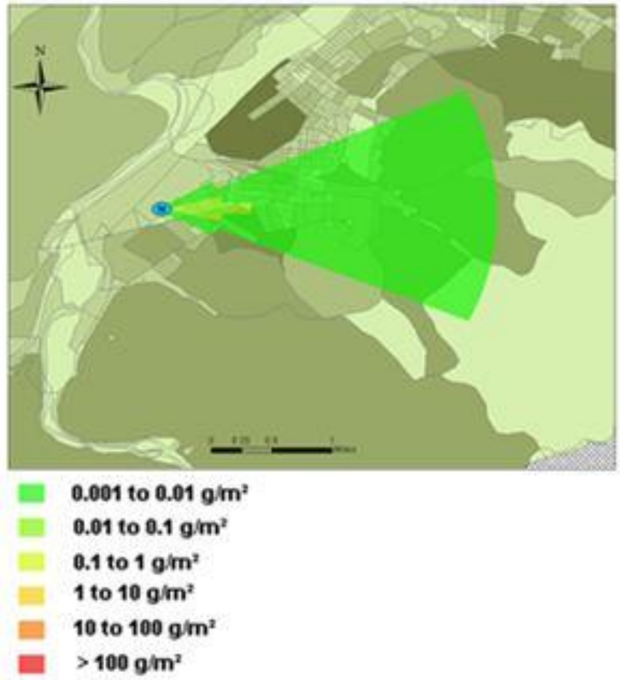


Figure B: HF Deposition plume for a 2.5 ton cylinder for the spring season

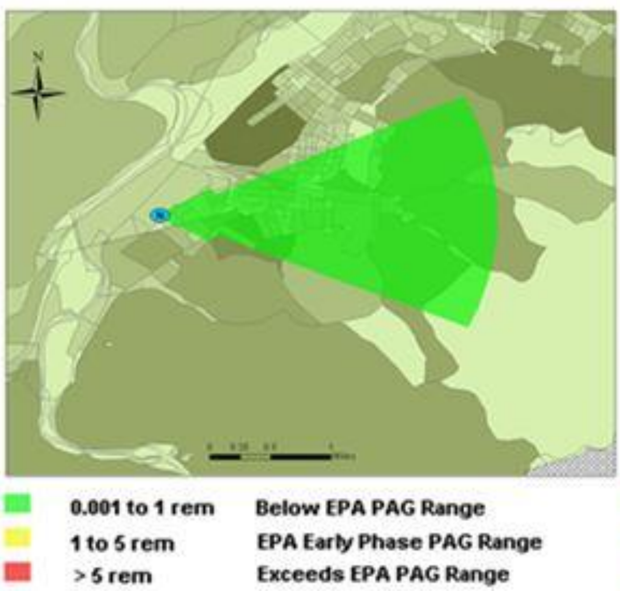


Figure C: Uranium concentration plume for a 2.5 ton cylinder for the spring season

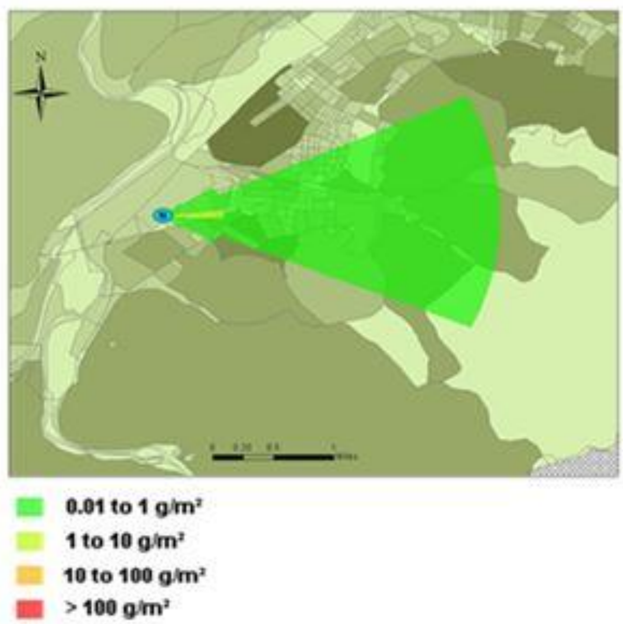


Figure D: Uranium deposition plume for a 2.5 ton cylinder for the spring season

Figure B.1: HF and uranium concentration and deposition plumes for a 2.5 ton cylinder rupture using seasonal mean data for the spring of 2012.

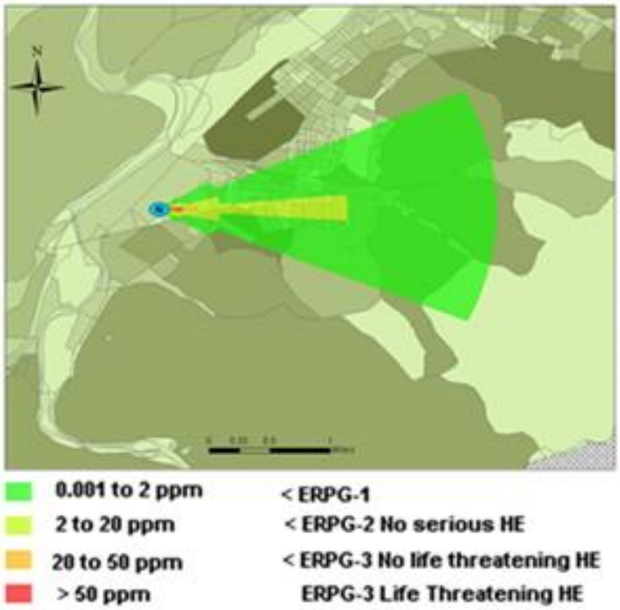


Figure A: HF concentration plume for a 10 ton cylinder for the spring season.

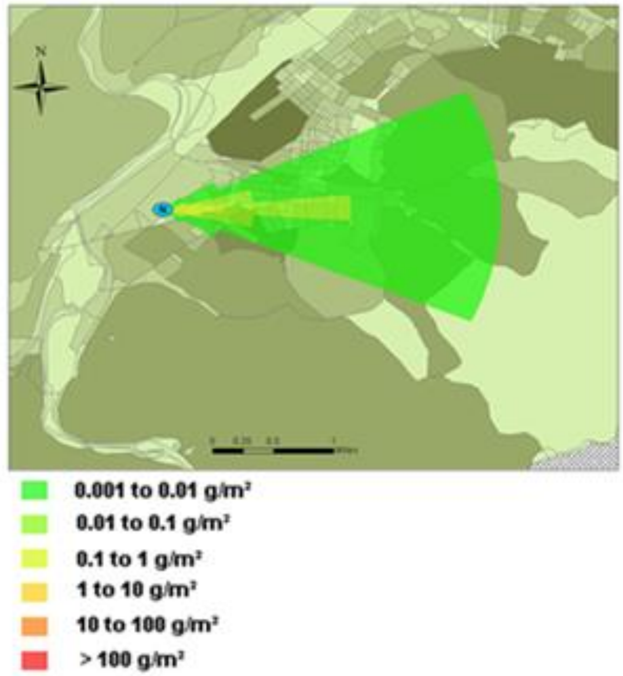


Figure B: HF deposition plume for a 10 ton cylinder for the spring season.

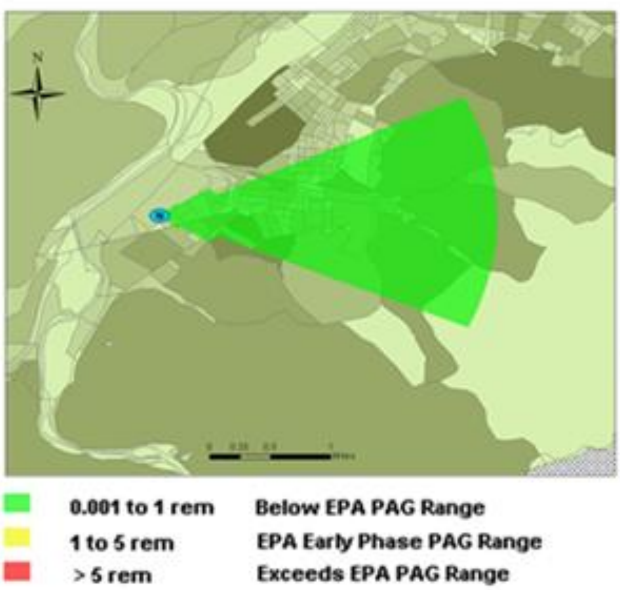


Figure C: Uranium concentration plume for a 10 ton cylinder for the spring season.

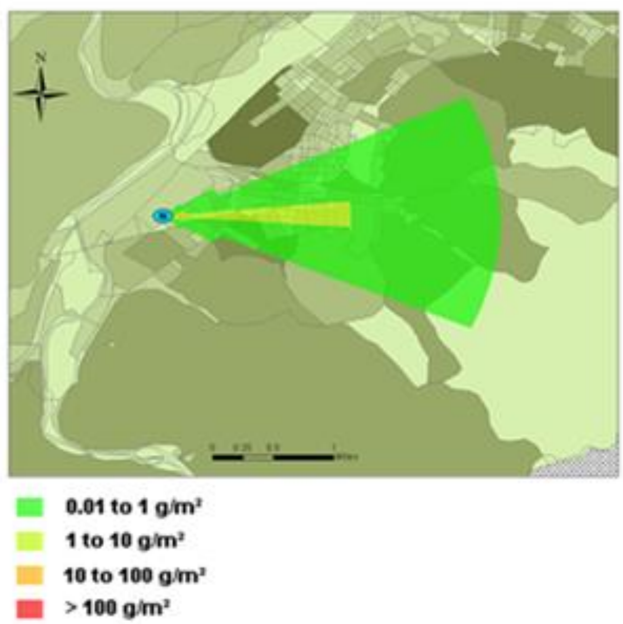


Figure D: Uranium deposition plume for a 10 ton cylinder for the spring season.

Figure B.2: HF and uranium concentration and deposition plumes for a 10 ton cylinder rupture using seasonal mean data for the spring of 2012.

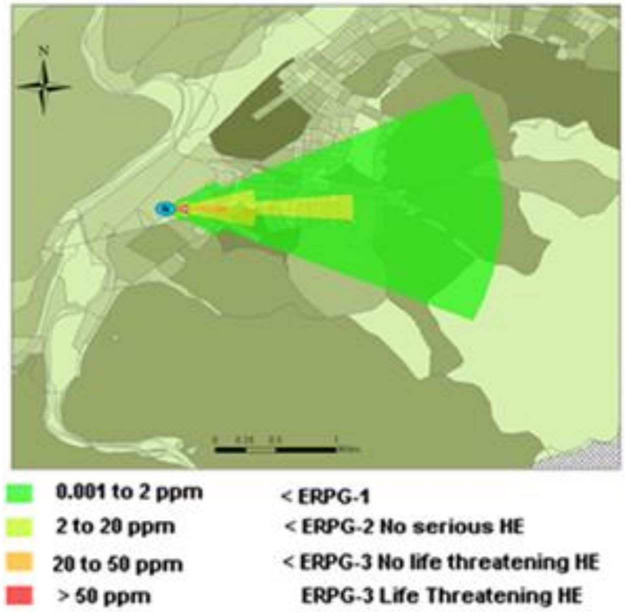


Figure A: HF concentration plume for a 14 ton cylinder for the spring season.

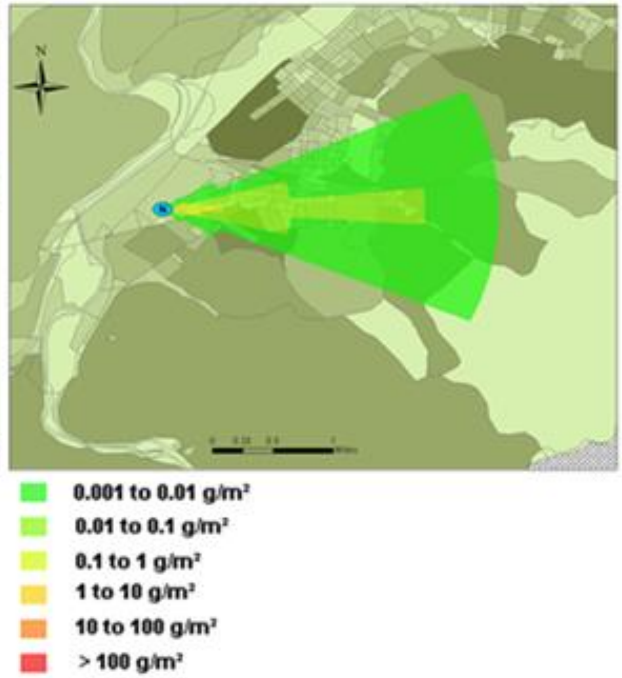


Figure B: HF deposition plume for a 14 ton cylinder for the spring season.

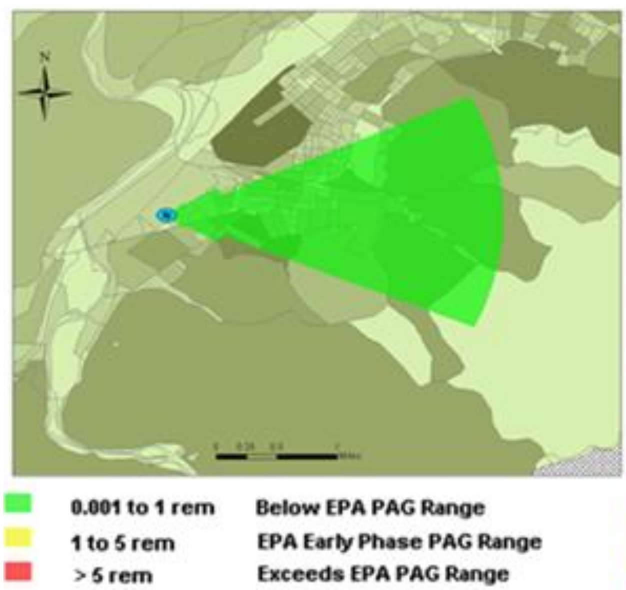


Figure C: Uranium concentration plume for a 14 ton cylinder for the spring season.

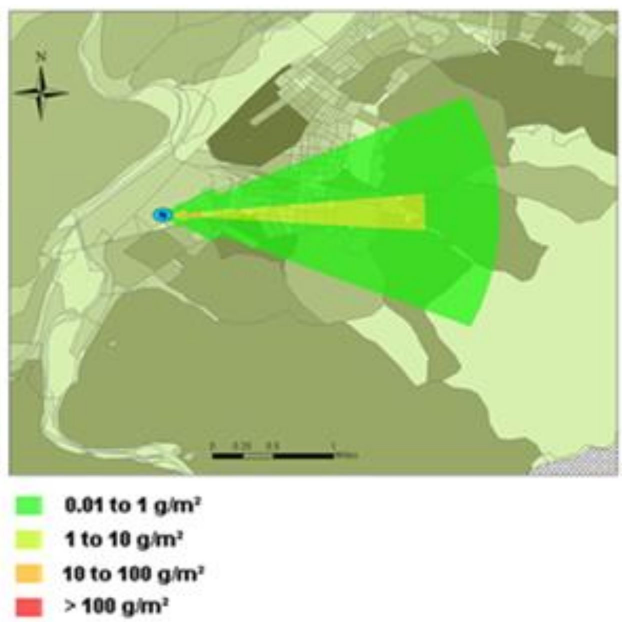


Figure D: Uranium deposition plume for a 14 ton cylinder for the spring season.

Figure B.3: HF and uranium concentration and deposition plumes for a 14 ton cylinder rupture using seasonal mean data for the spring of 2012.

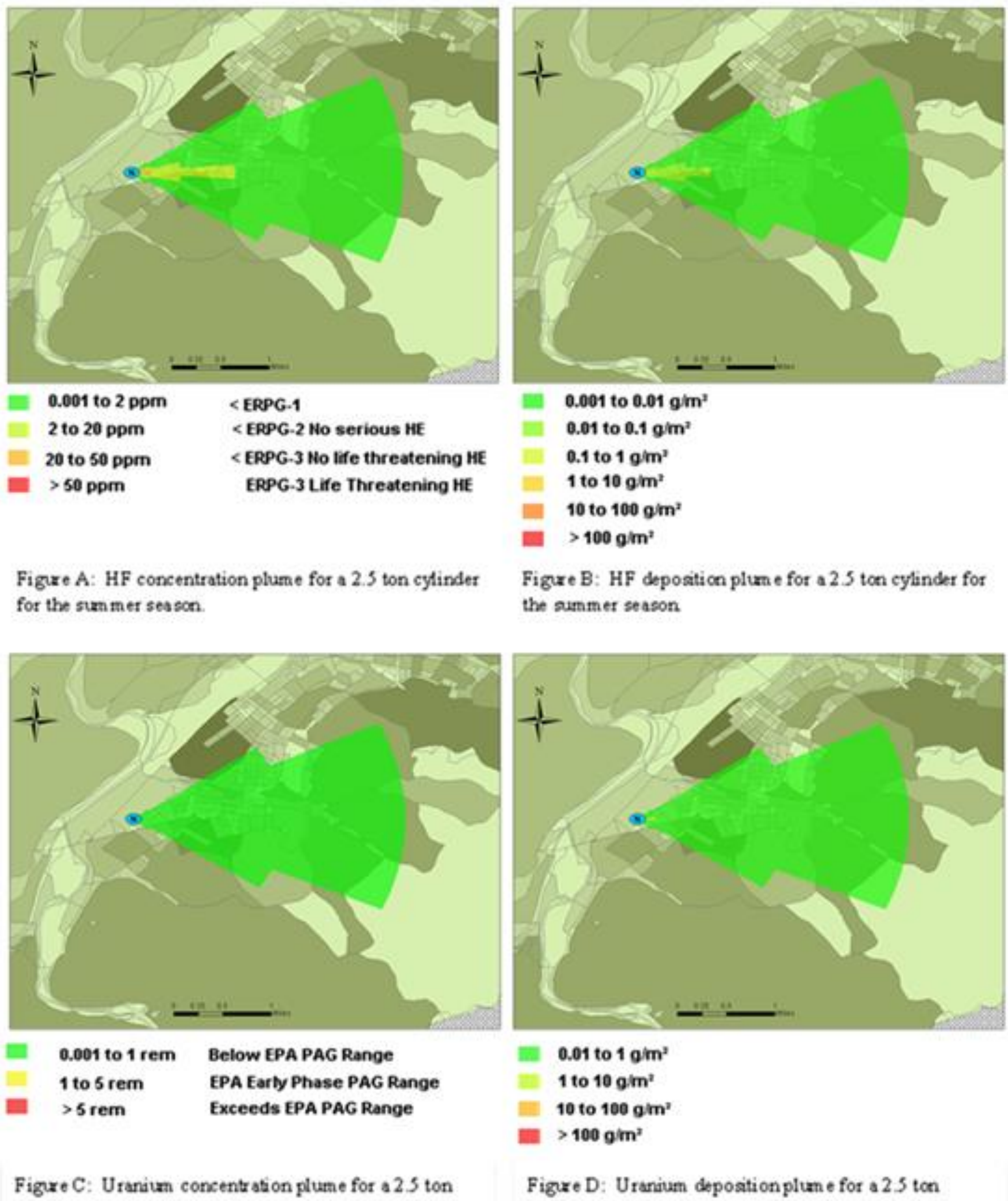


Figure A: HF concentration plume for a 2.5 ton cylinder for the summer season.

Figure B: HF deposition plume for a 2.5 ton cylinder for the summer season.

Figure C: Uranium concentration plume for a 2.5 ton cylinder for the summer season.

Figure D: Uranium deposition plume for a 2.5 ton cylinder for the summer season.

Figure B.4: HF and uranium concentration and deposition plumes for a 2.5 ton cylinder rupture using seasonal mean data for the summer of 2012.

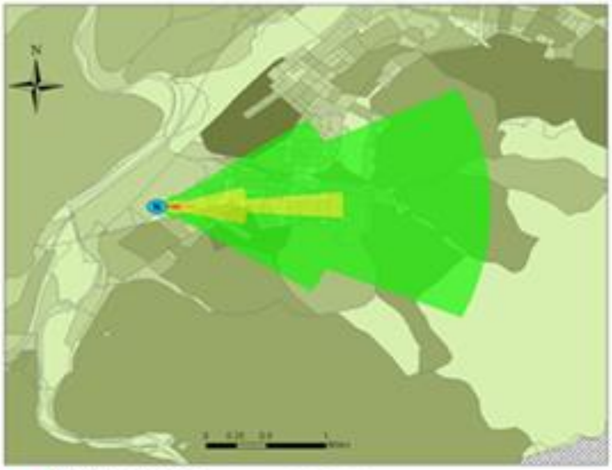


Figure A: HF concentration plume for a 10 ton cylinder for the summer season.

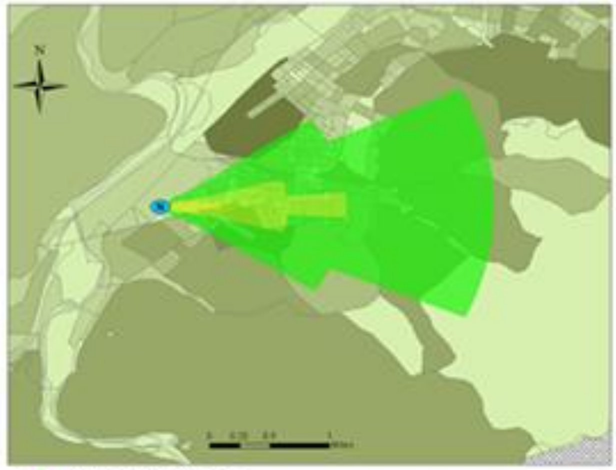


Figure B: HF deposition plume for a 10 ton cylinder for the summer season.

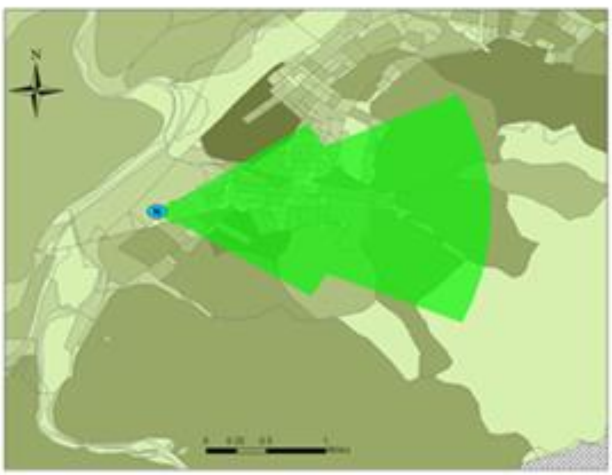


Figure C: Uranium concentration plume for a 10 ton cylinder for the summer season.

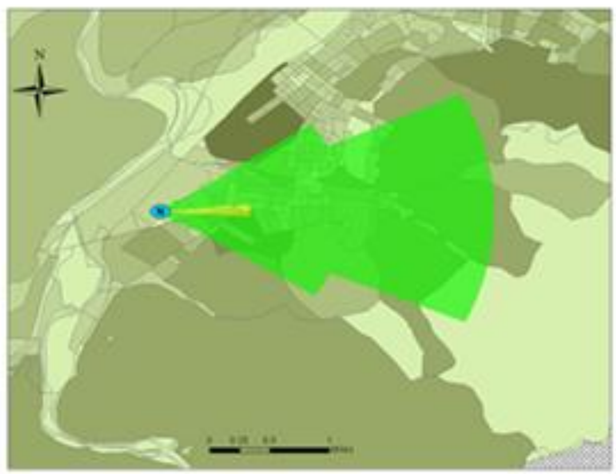


Figure D: Uranium deposition plume for a 10 ton cylinder for the summer season.

Figure B.5: HF and uranium concentration and deposition plumes for a 10 ton cylinder rupture using seasonal mean data for the summer of 2012.

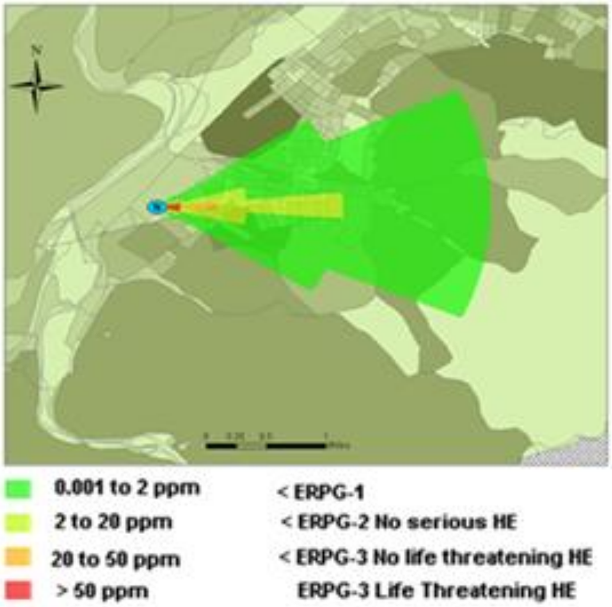


Figure A: HF concentration plume for a 14 ton cylinder for the summer season.

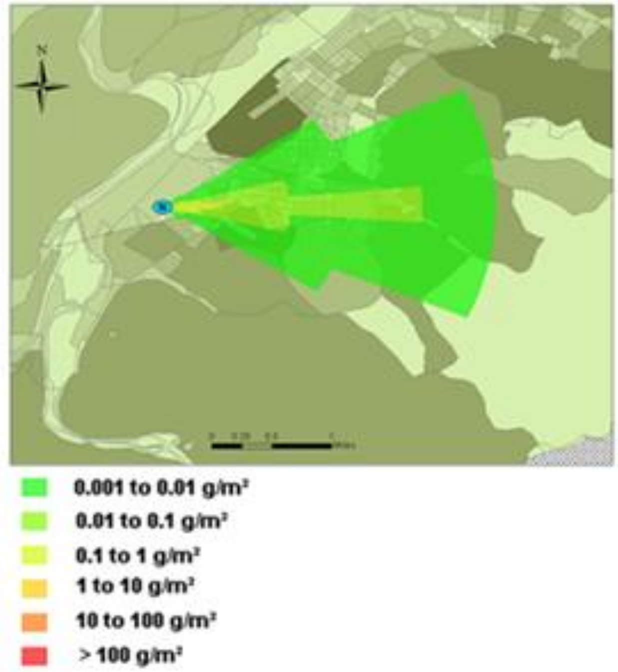


Figure B: HF deposition plume for a 14 ton cylinder for the summer season.

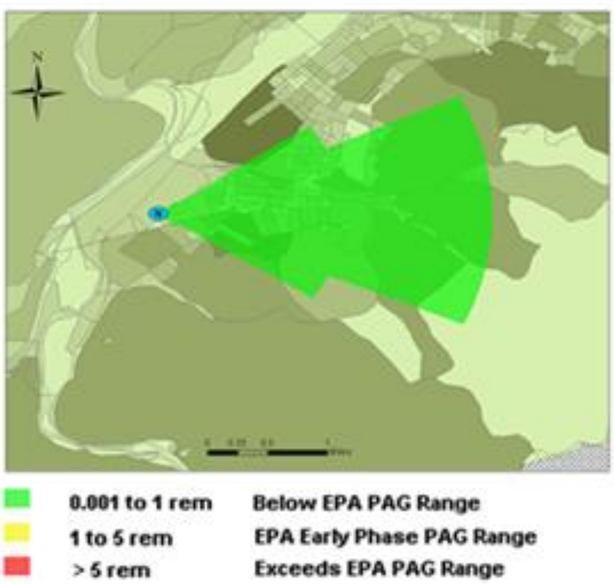


Figure C: Uranium concentration plume for a 14 ton cylinder for the summer season.

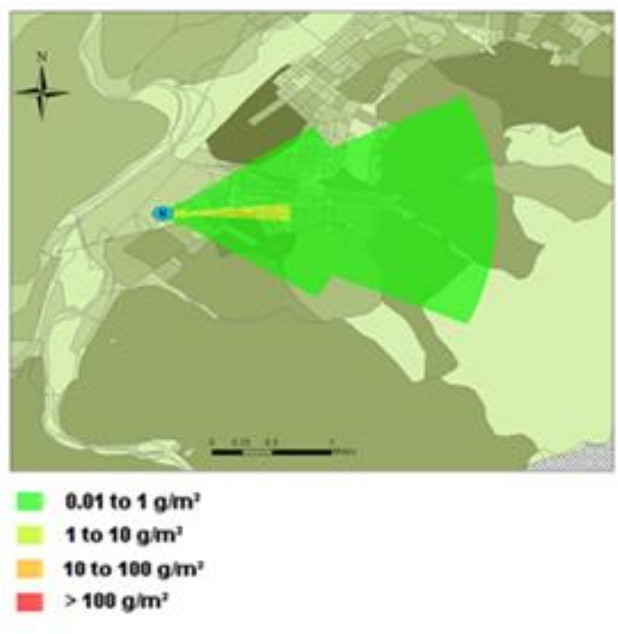


Figure D: Uranium deposition plume for a 14 ton cylinder for the summer season.

Figure B.6: HF and uranium concentration and deposition plumes for a 14 ton cylinder rupture using seasonal mean data for the summer of 2012.

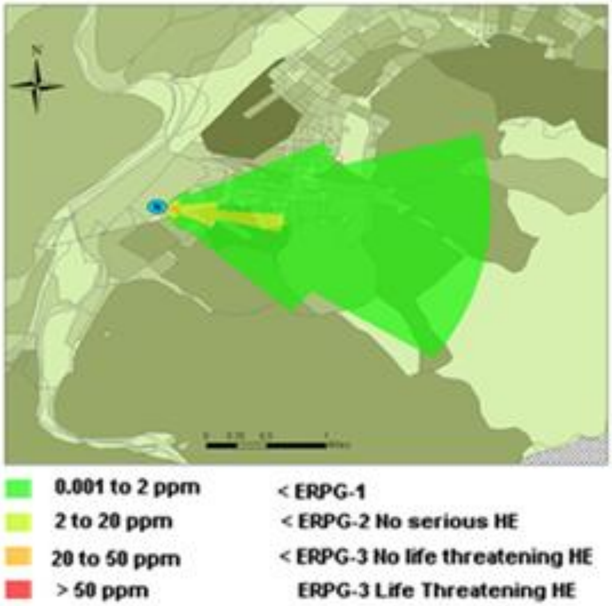


Figure A: HF concentration plume for a 2.5 ton cylinder for the autumn season.

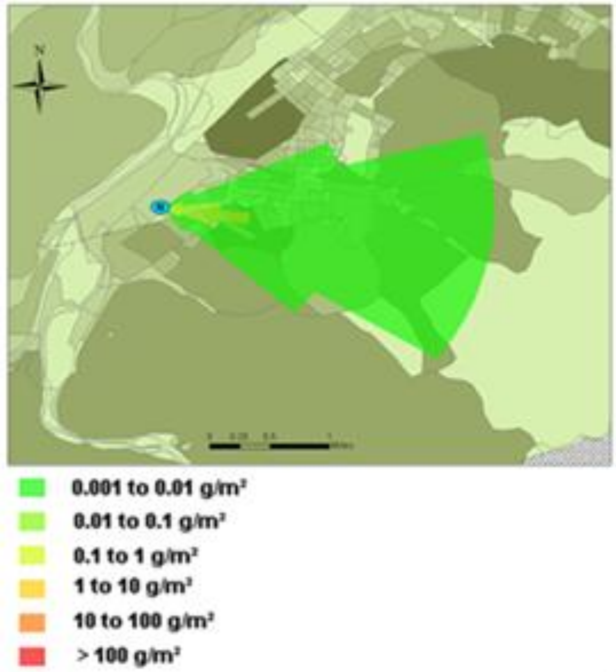


Figure B: HF deposition plume for a 2.5 ton cylinder for the autumn season.

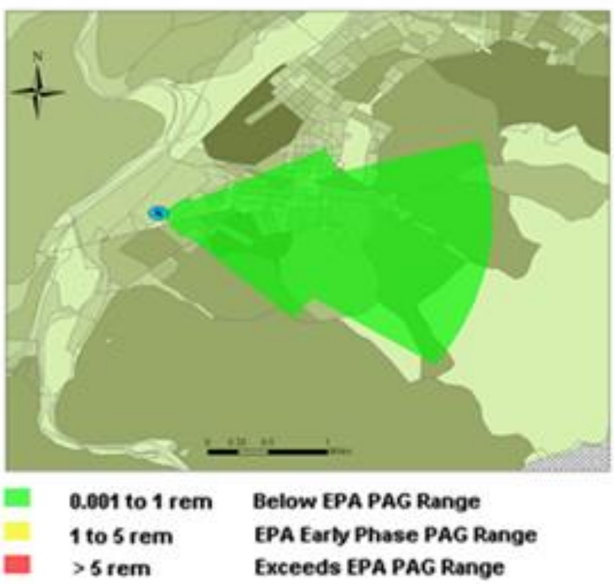


Figure C: Uranium concentration plume for a 2.5 ton cylinder for the autumn season.

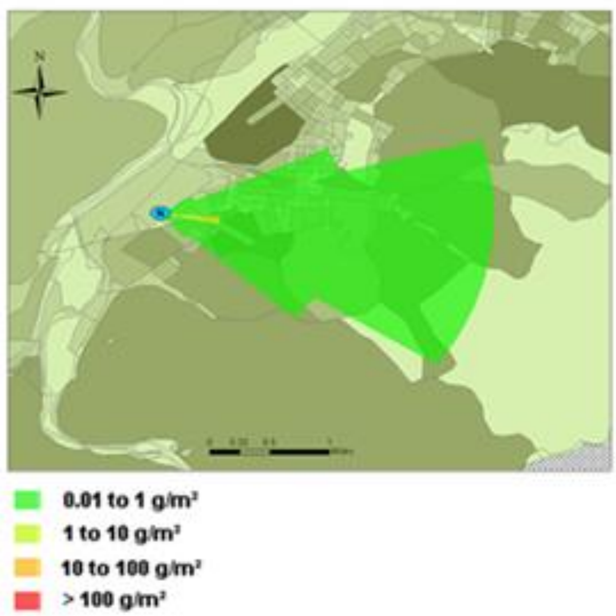


Figure D: Uranium deposition plume for a 2.5 ton cylinder for the autumn season.

Figure B.7: HF and uranium concentration and deposition plumes for a 2.5 ton cylinder rupture using seasonal mean data for the autumn of 2012.

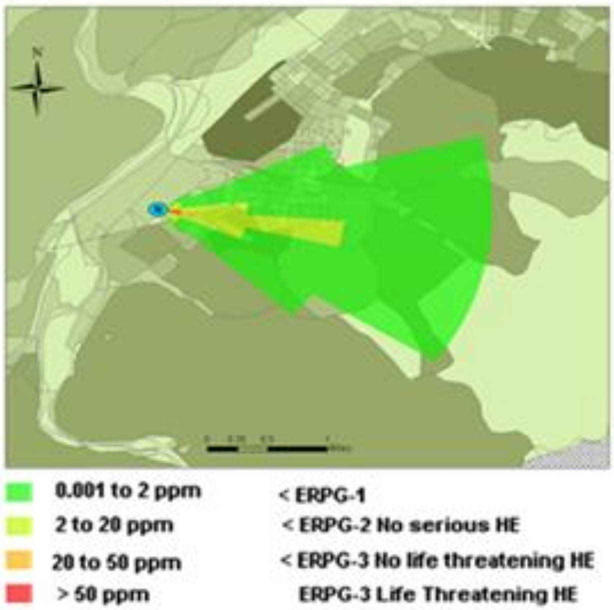


Figure A: HF concentration plume for a 10 ton cylinder for the autumn season.

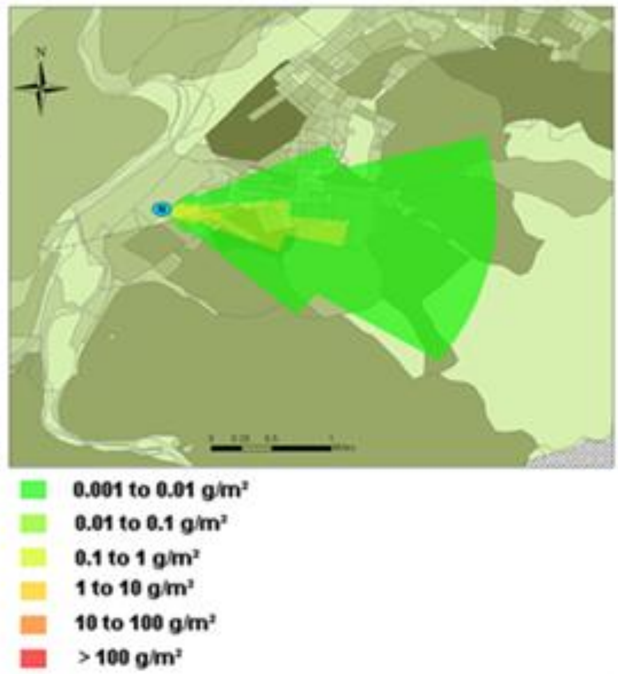


Figure B: HF deposition plume for a 10 ton cylinder for the autumn season.

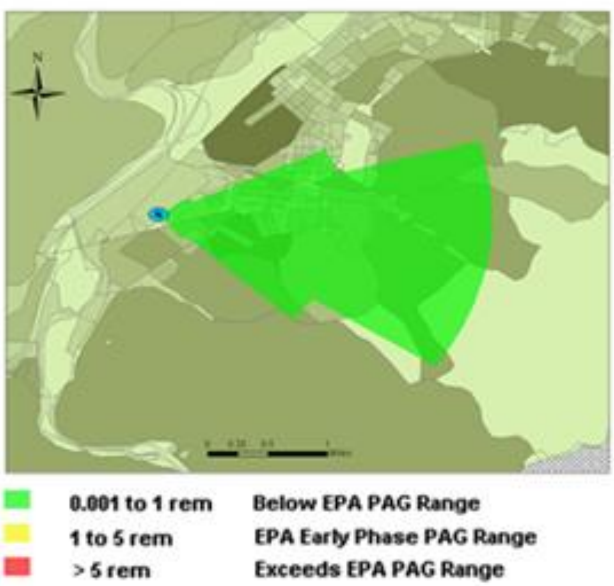


Figure C: Uranium concentration plume for a 10 ton cylinder for the autumn season.

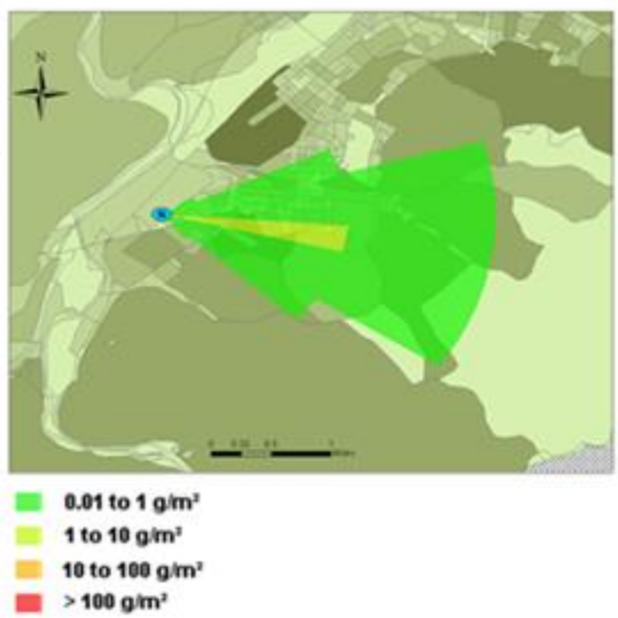


Figure D: Uranium deposition plume for a 10 ton cylinder for the autumn season.

Figure B.8: HF and uranium concentration and deposition plumes for a 10 ton cylinder rupture using seasonal mean data for the autumn of 2012.

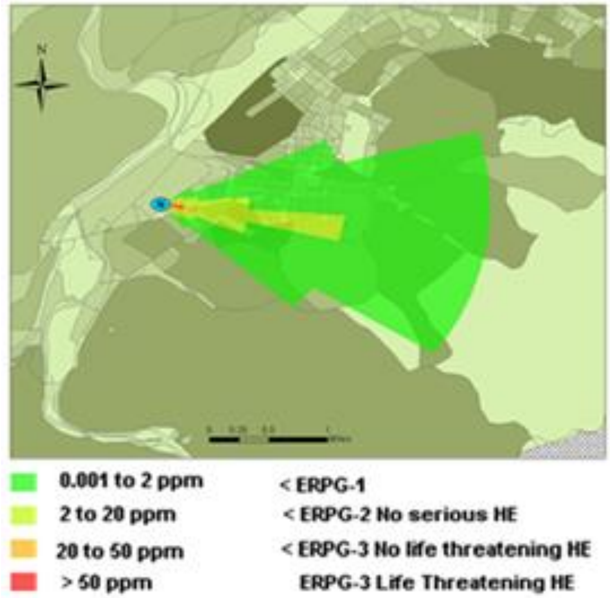


Figure A: HF concentration plume for a 14 ton cylinder for the autumn season.

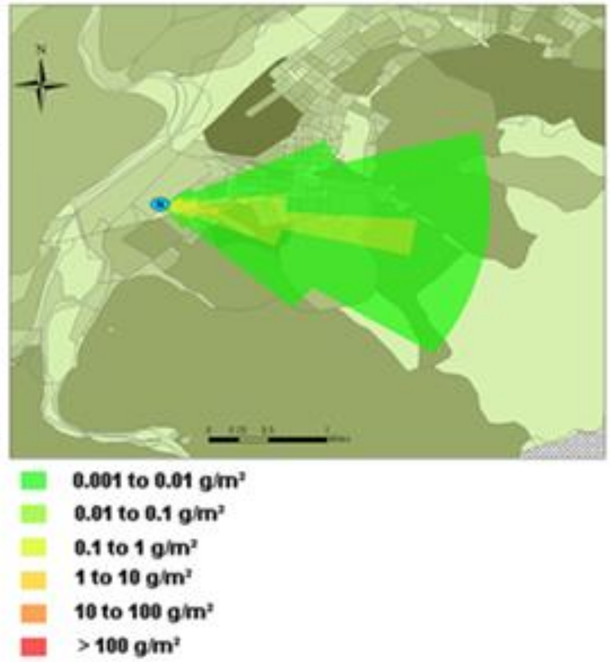


Figure B: HF deposition plume for a 14 ton cylinder for the autumn season.

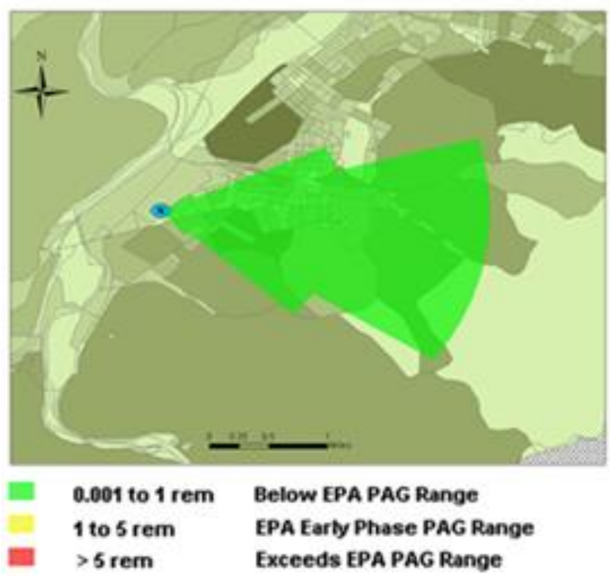


Figure C: Uranium concentration plume for a 14 ton cylinder for the autumn season.

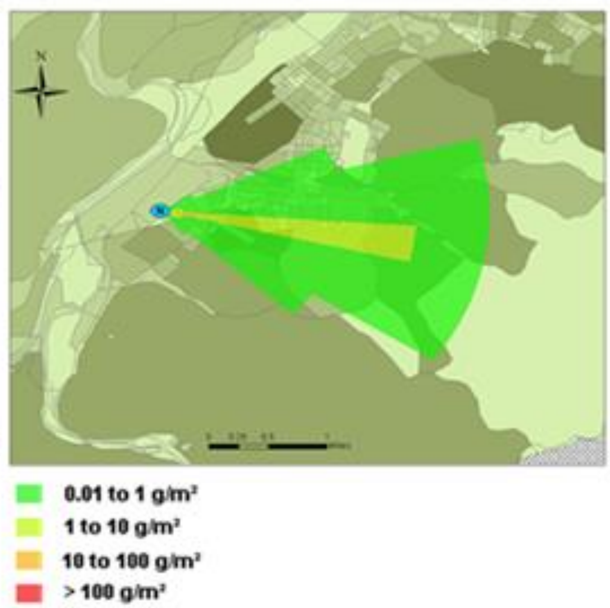


Figure D: Uranium deposition plume for a 14 ton cylinder for the autumn season.

Figure B.9: HF and uranium concentration and deposition plumes for a 14 ton cylinder rupture using seasonal mean data for the autumn of 2012.

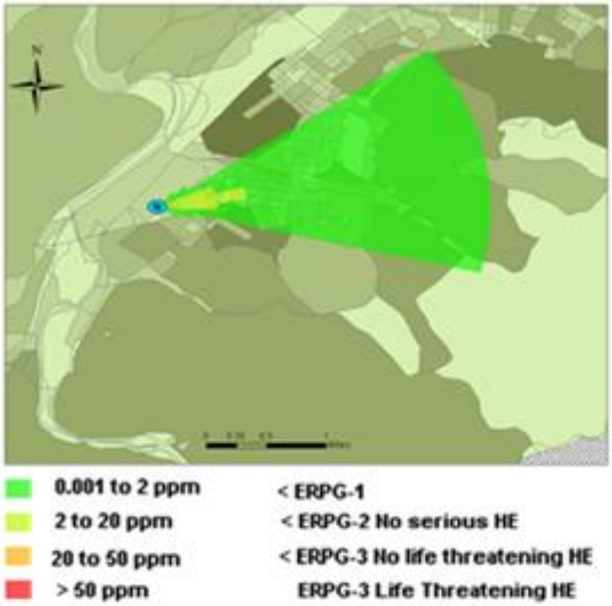


Figure A: HF concentration plume for a 2.5 ton cylinder for the winter season.

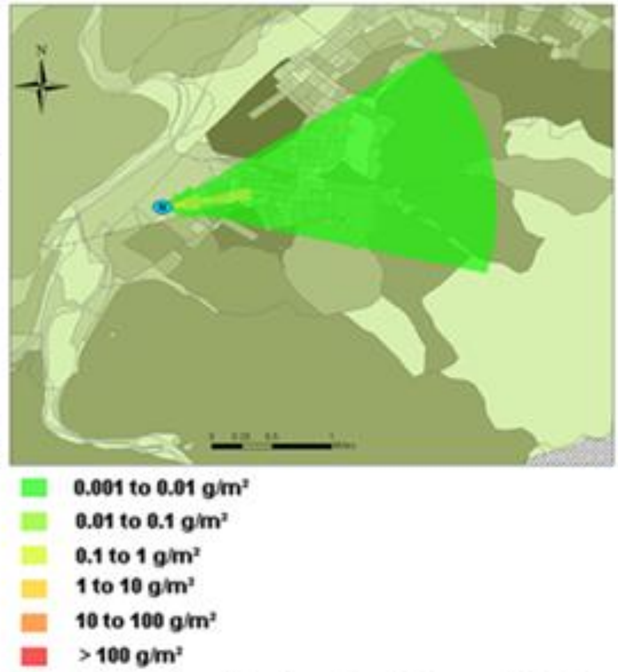


Figure B: HF deposition plume for a 2.5 ton cylinder for the winter season.

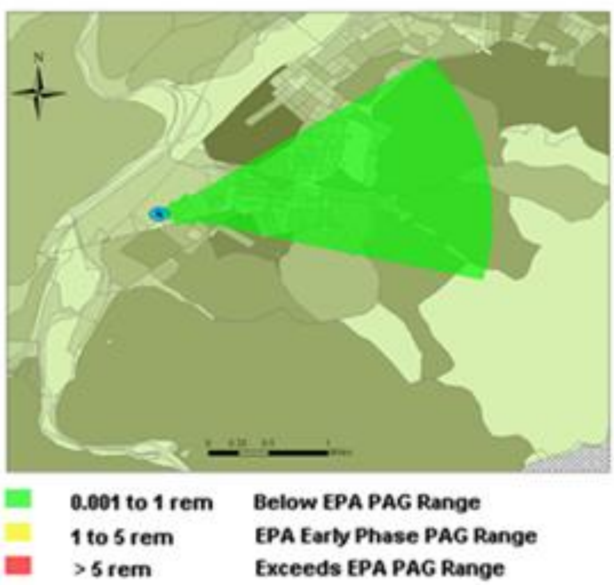


Figure C: Uranium concentration plume for a 2.5 ton cylinder for the winter season.

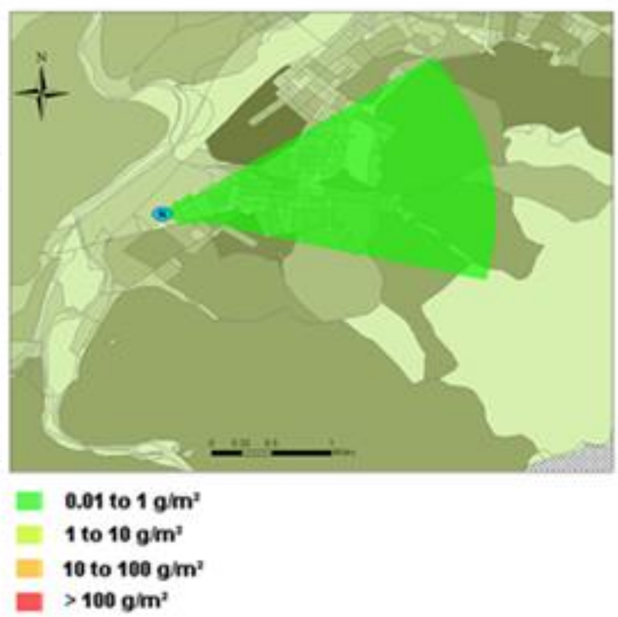


Figure D: Uranium deposition plume for a 2.5 ton cylinder for the winter season.

Figure B.10: HF and uranium concentration and deposition plumes for a 2.5 cylinder rupture using seasonal mean data for the winter of 2012.

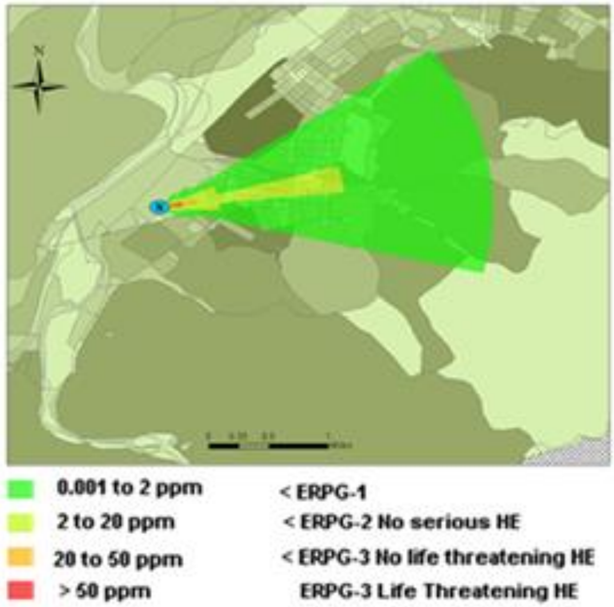


Figure A: HF concentration plume for a 10 ton cylinder for the winter season.

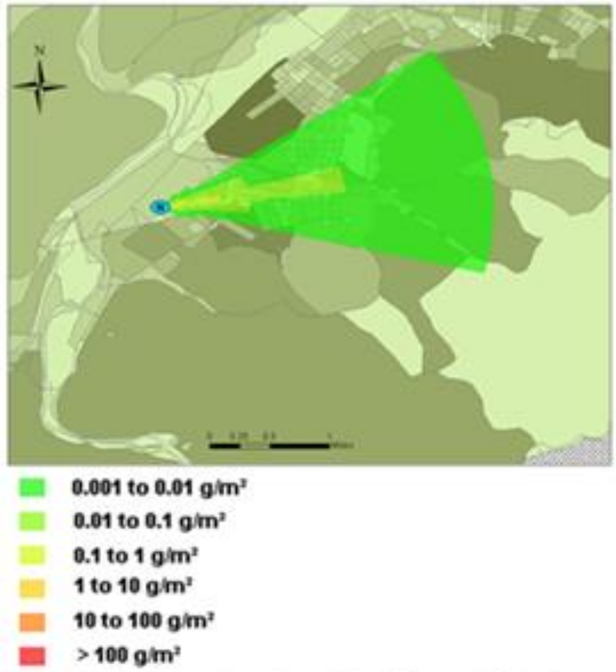


Figure B: HF deposition plume for a 10 ton cylinder for the winter season.

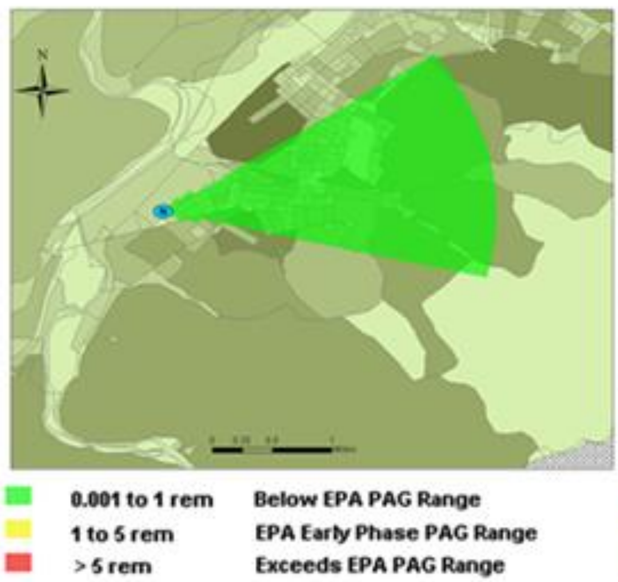


Figure C: Uranium concentration plume for a 10 ton cylinder for the winter season.

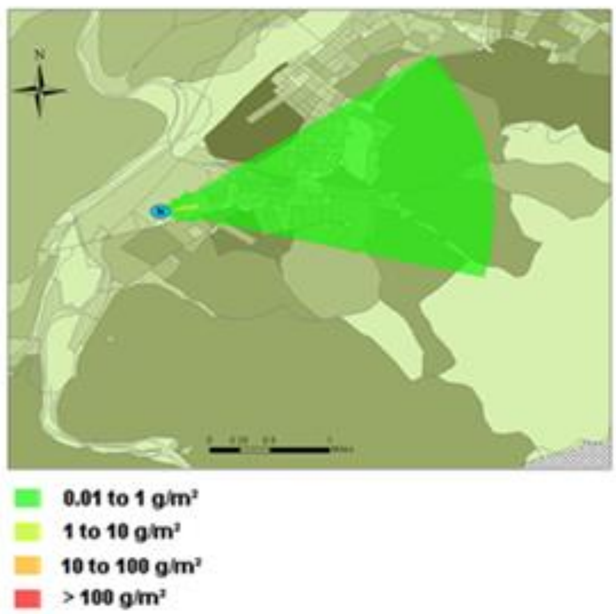


Figure D: Uranium deposition plume for a 10 ton cylinder for the winter season.

Figure B.11: HF and uranium concentration and deposition plumes for a 10 ton cylinder rupture using seasonal mean data for the winter of 2012.

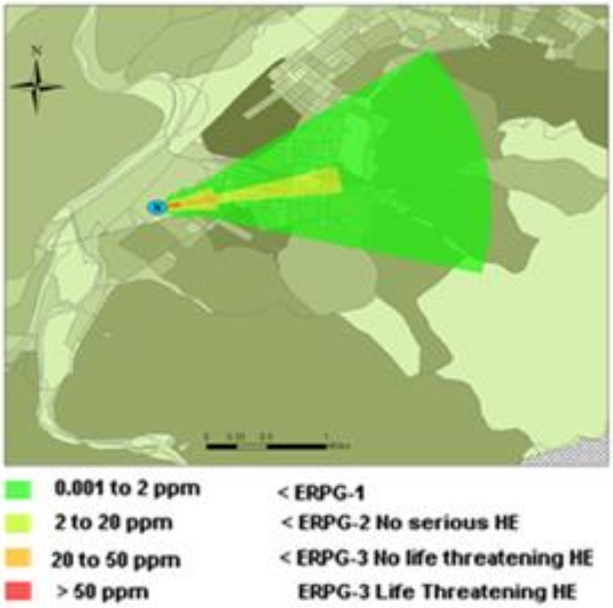


Figure A: HF concentration plume for a 14 ton cylinder for the winter season.

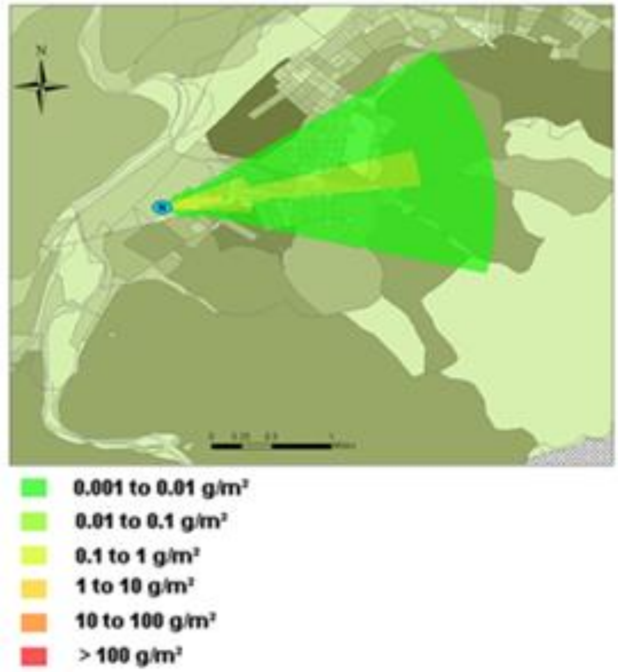


Figure B: HF deposition plume for a 14 ton cylinder for the winter season.

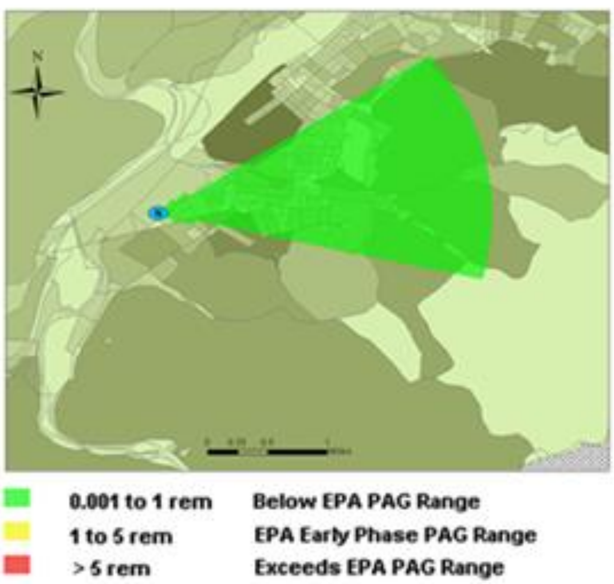


Figure C: Uranium concentration plume for a 14 ton cylinder for the winter season.

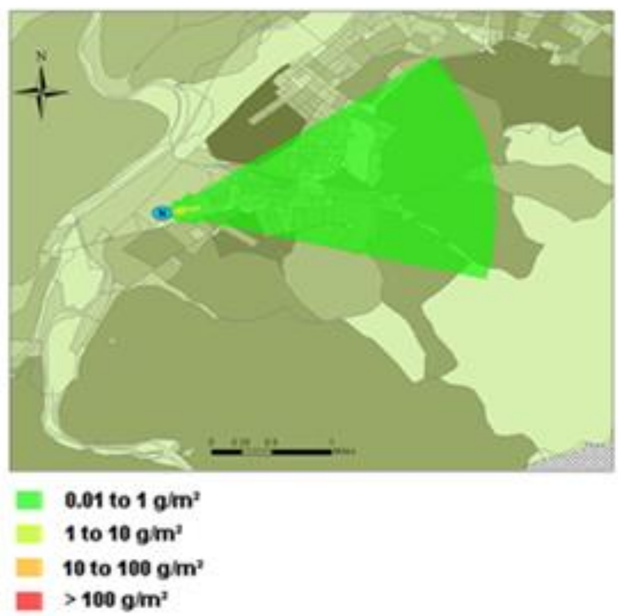


Figure D: Uranium deposition plume for a 14 ton cylinder for the winter season.

Figure B.12: HF and uranium concentration and deposition plumes for a 14 ton cylinder rupture using seasonal mean data for the winter of 2012.

VITA

JOSEPH BLAKE HARRIS

Education:	M.S. Geosciences, East Tennessee State University, Johnson City, Tennessee 2014
	B.S. Geosciences, Austin Peay State University, Clarksville, Tennessee 2012
	A.S. Hopkinsville Community College, Hopkinsville, Kentucky 2009
	Christian Liberty Academy, Arlington Heights, Illinois
Professional Societies:	Association of American Geographers
	Geological Society of America
	American Geophysical Union
Employment:	GIS Help Desk Manager, ETSU, Spring 2014
	Graduate Assistant, ETSU, Fall 2012
Posters:	2013 Appalachian Research Forum – ETSU (April 4, 2013) A statistical and GIS approach to analyzing a museums customer base.
*	2014 Appalachian Research Forum – ETSU (April 3, 2013) Evacuation and sheltering in place modeling for a release of uranium hexafluoride.
	(* = First Place in Natural Science Category)